NuCubes:
R&D towards a 3D Water-Based Liquid Scintillator near detector for Hyper-Kamiokande

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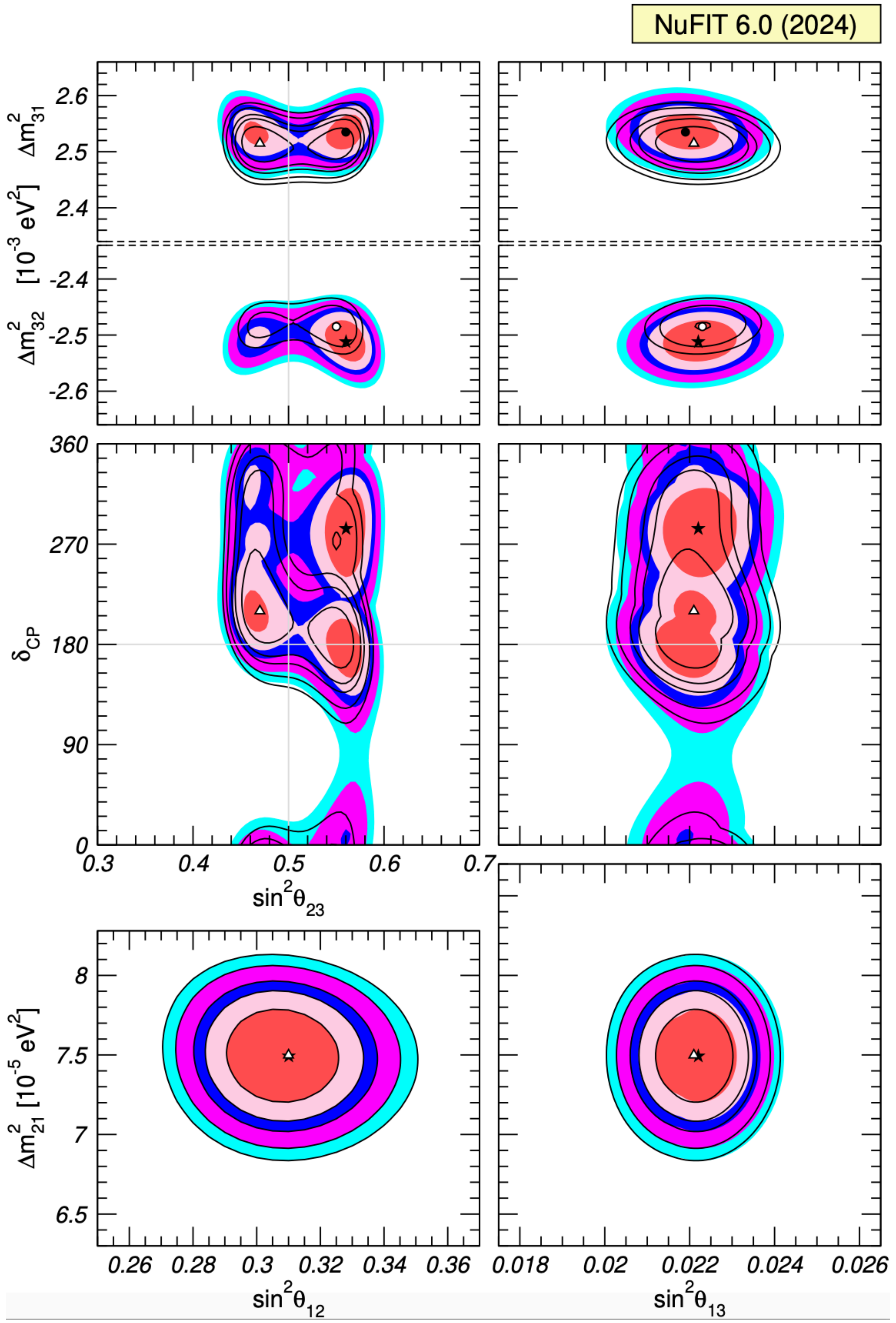
Neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics and LBL
$\theta_{23} \sim 45°$
$|\Delta m^2_{32}| \sim 2.5\times10^{-3}$ eV^2

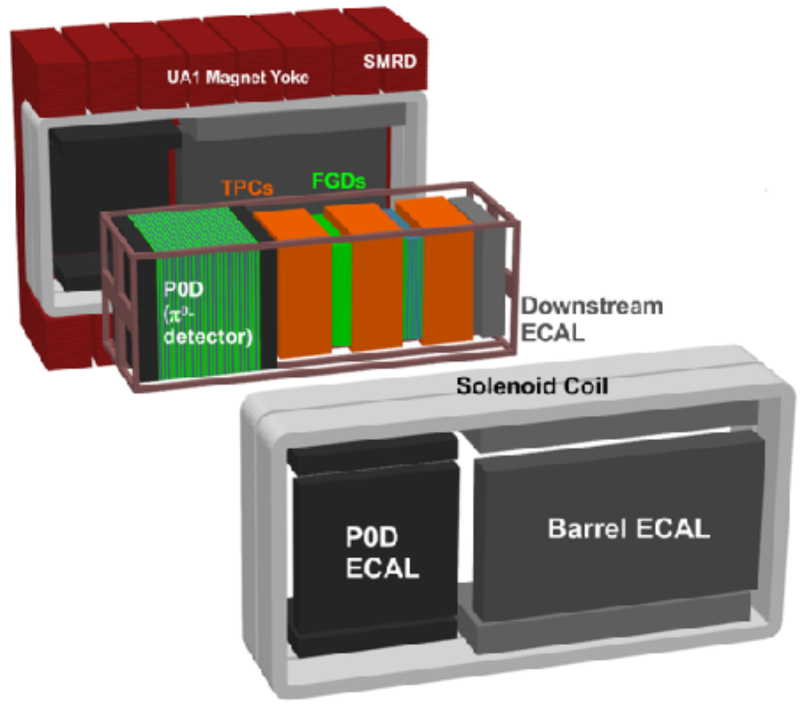
Reactors $\theta_{13} \sim 10°$
LBL θ_{13} and δ_{CP}

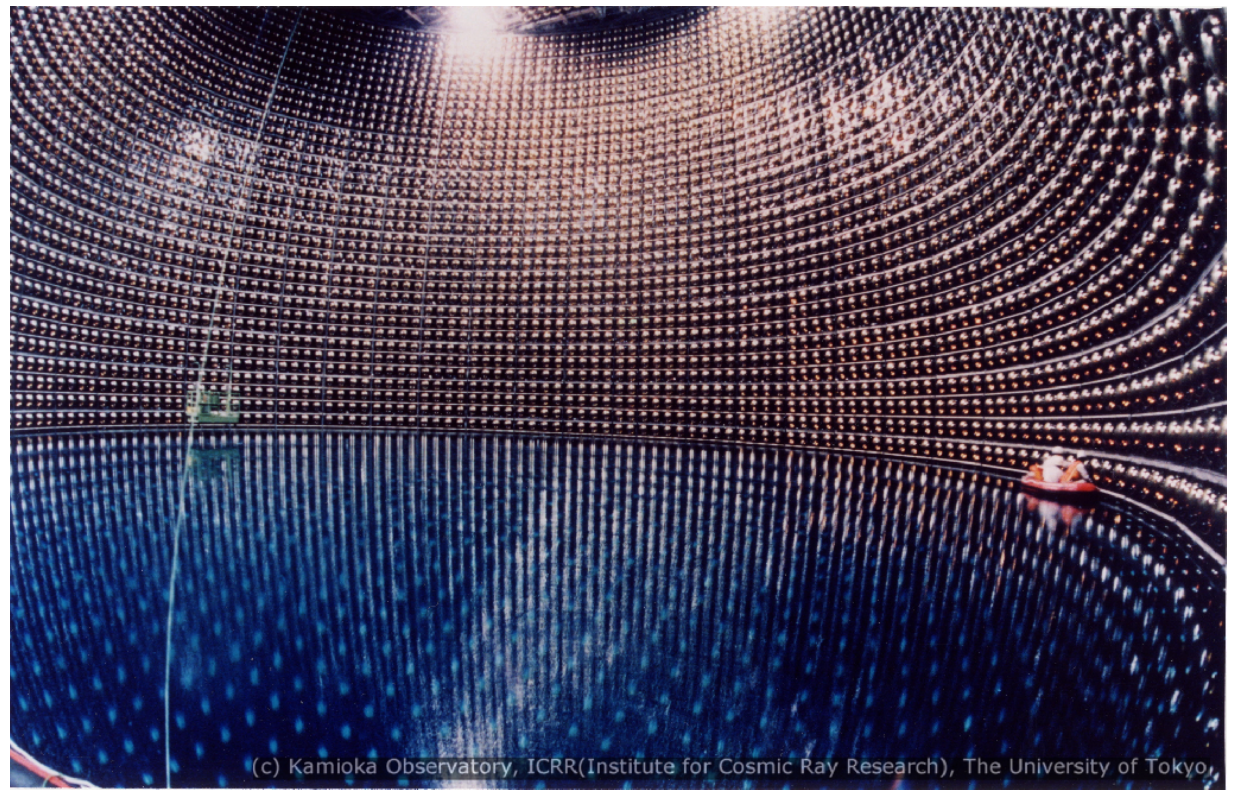
Solar and reactors
$\theta_{12} \sim 35°$ - $\Delta m^2_{21} \sim 7.5\times10^{-5}$ eV^2

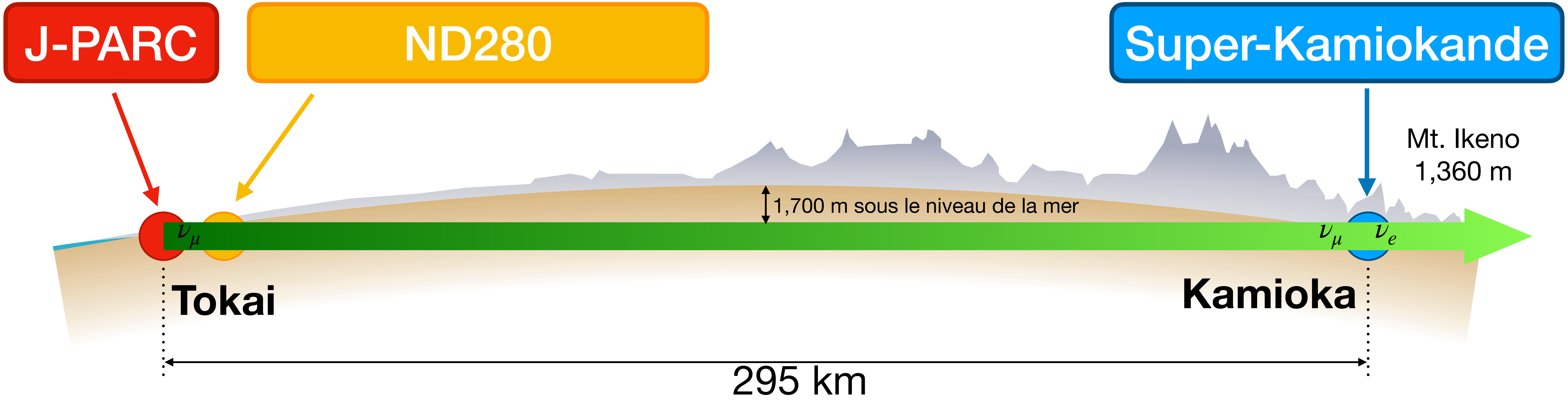


- Long baseline (LBL) experiments sensitive to 5 of the PMNS parameters
  - θ_{23}, $|\Delta m^2_{32}|$ → LBL provides the most precise measurements of these parameters
  - θ_{13} → dominated by reactor experiments
  - δ_{CP} and sign of Δm^2_{32} (normal or inverted ordering) → still unknown and accessible to LBL
- 2 new LBL experiments will start taking data in the next years:
  - Hyper-Kamiokande in Japan (2028)
  - DUNE in the US (2031)

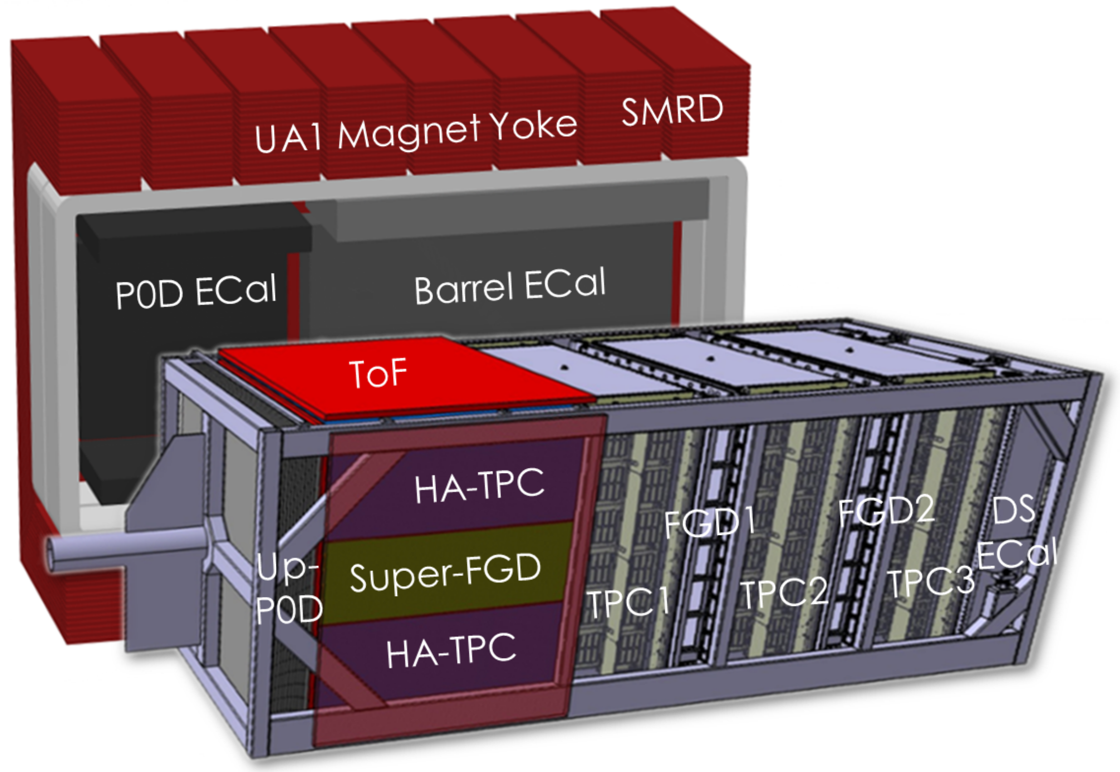
T2K (2010-2022)

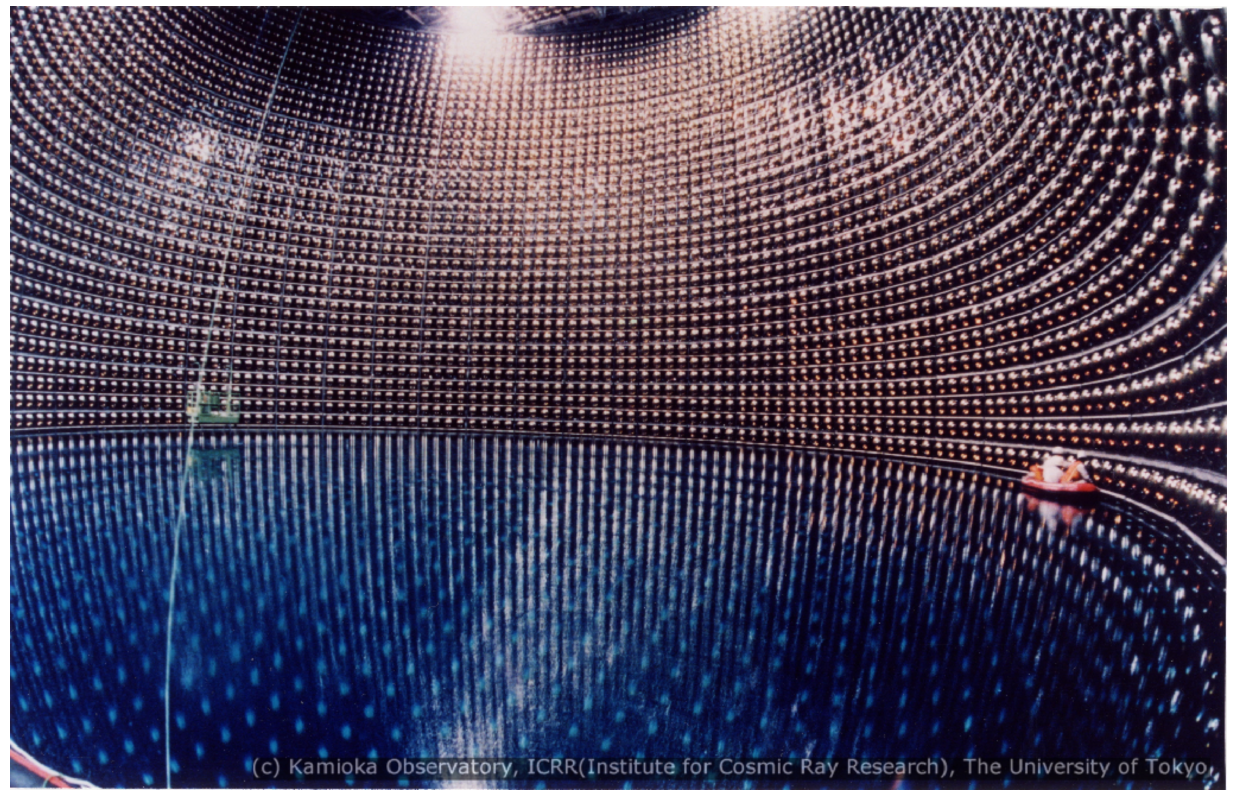






T2K ND280-upgrade (2023)

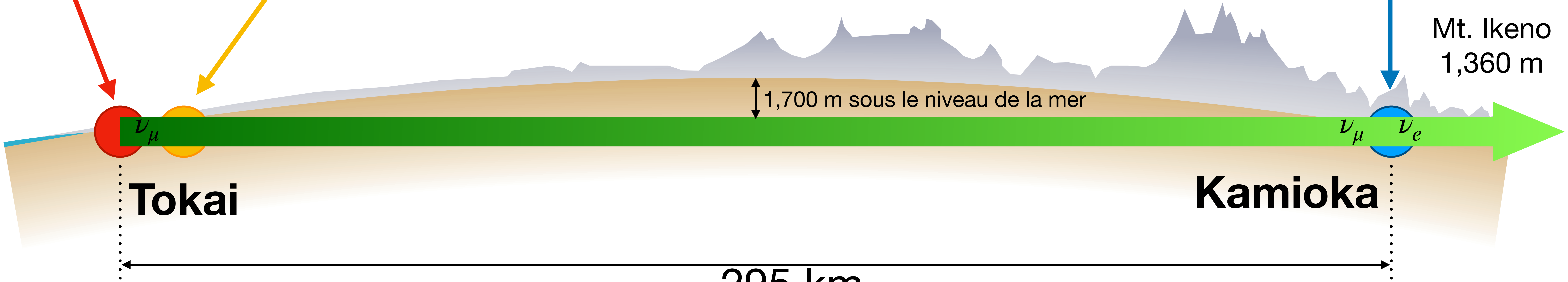




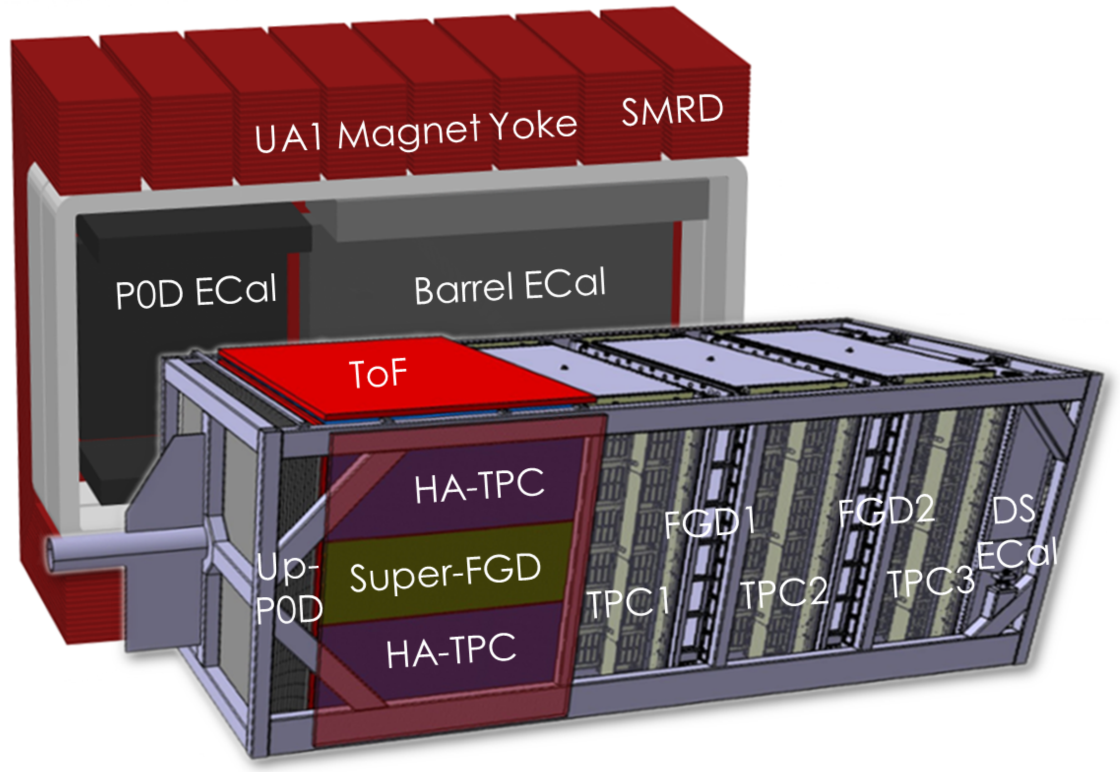
J-PARC

ND280-upgrade

Super-Kamiokande



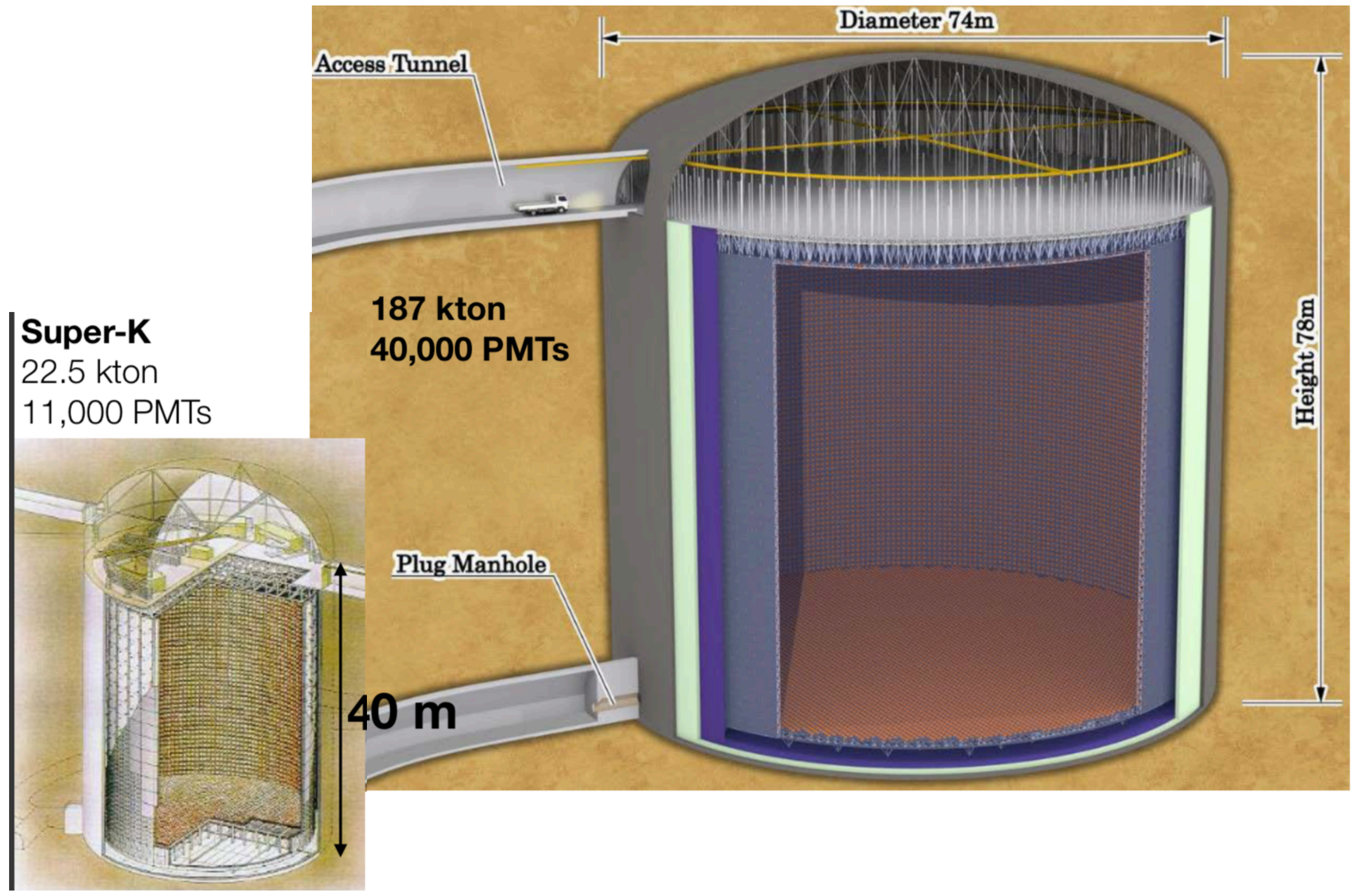
Hyper-Kamiokande (2028)



Hyper-K: $\sim 8 \times$ SK FV

Beam power: $\sim 2 \times$ T2K

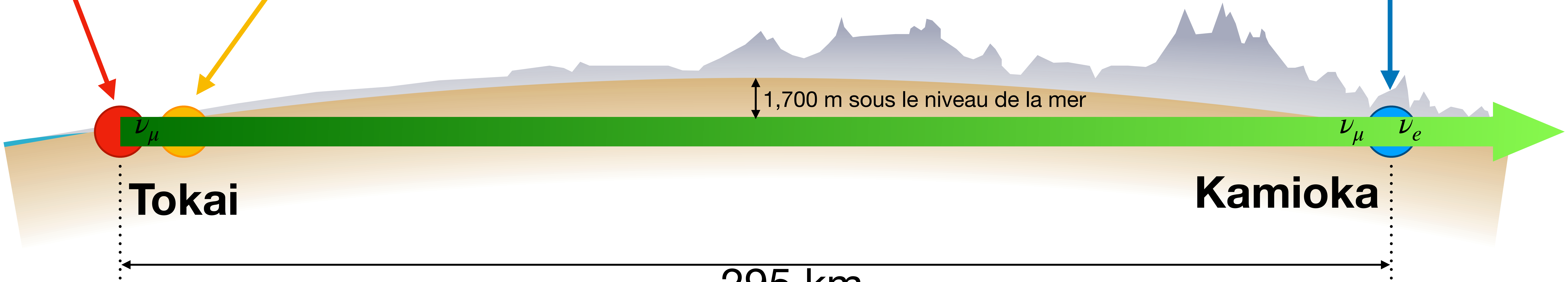
1 y HK ~ 20 y T2K



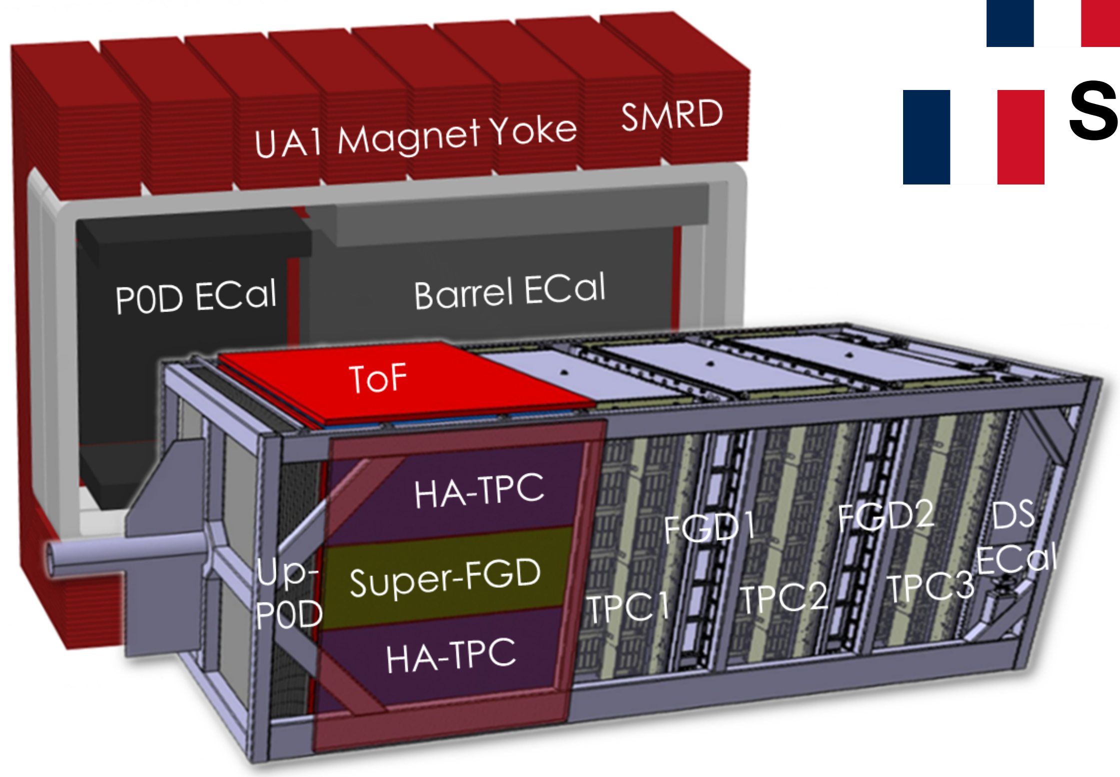
J-PARC

ND280-upgrade

Hyper-Kamiokande



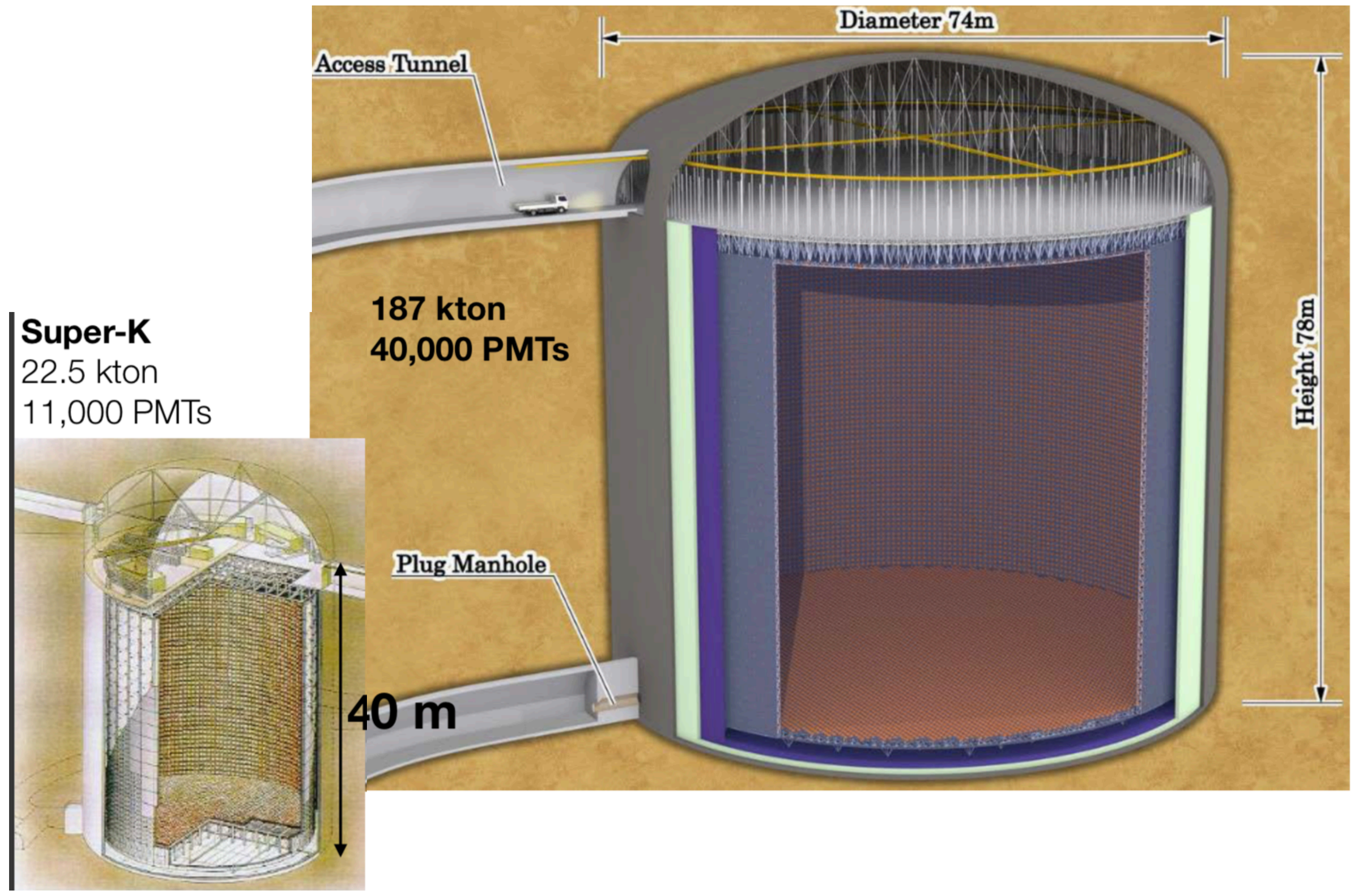
France/Italy contributions



HA-TPCs

Super-FGD electronics

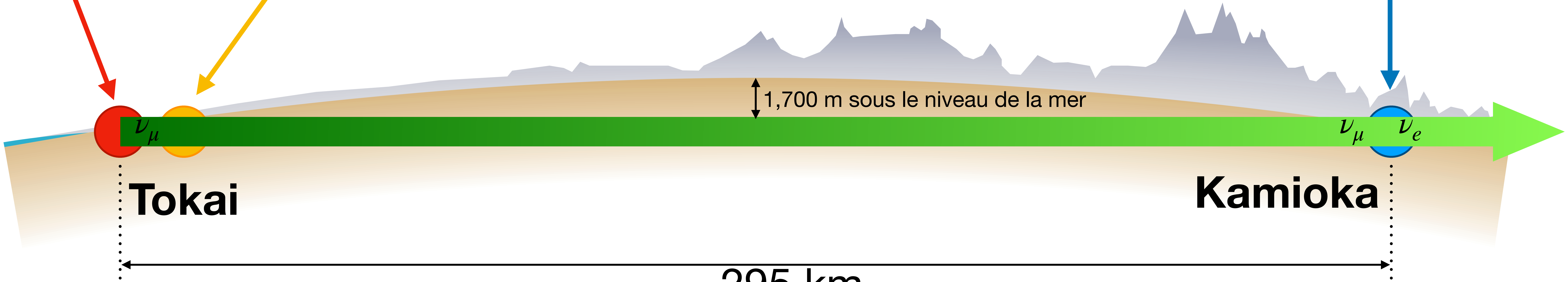
- HK electronics
  - ID Digitizer
  - Digitizer Calibration
  - Time synchronization system
- multi-PMTs



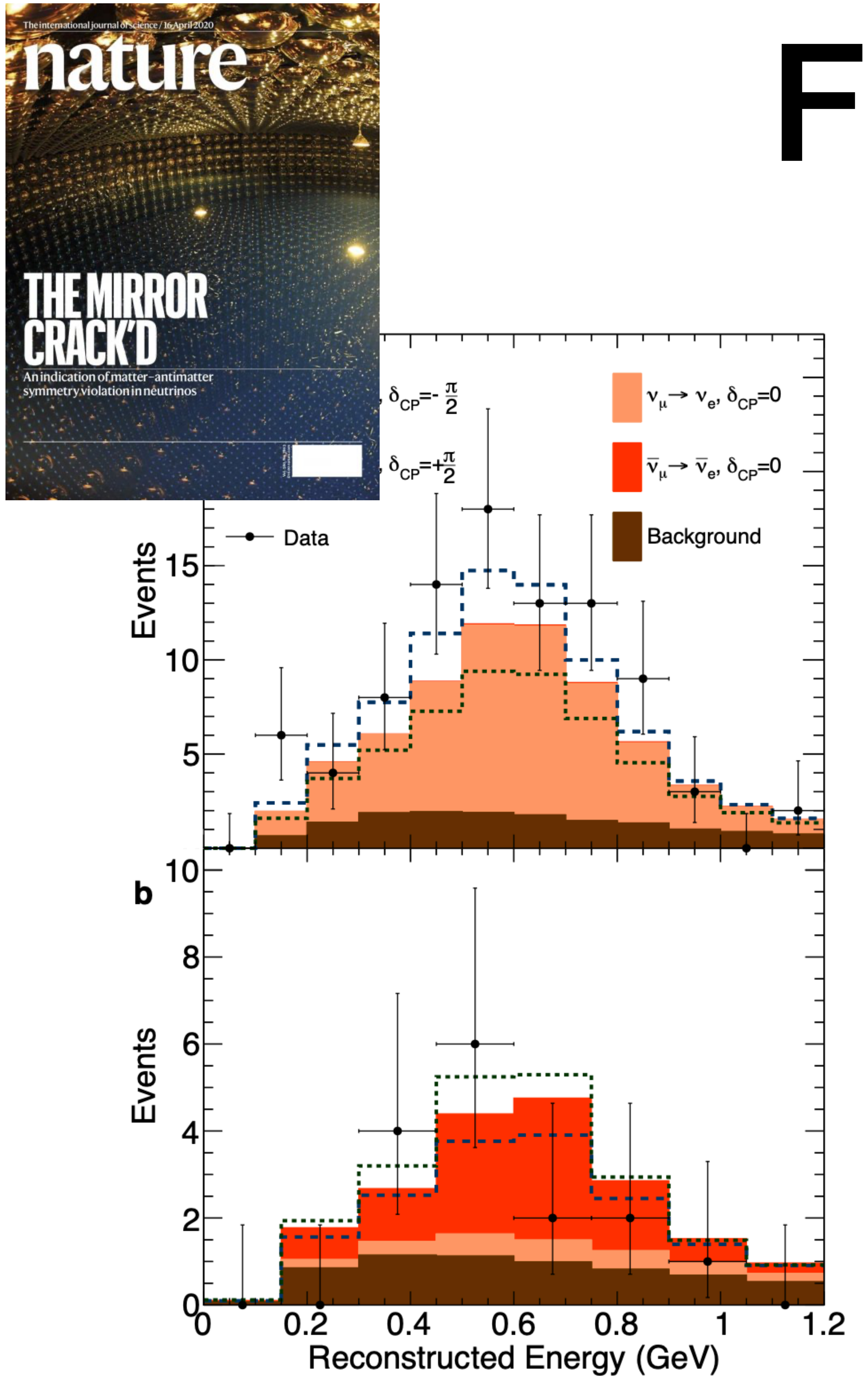
J-PARC

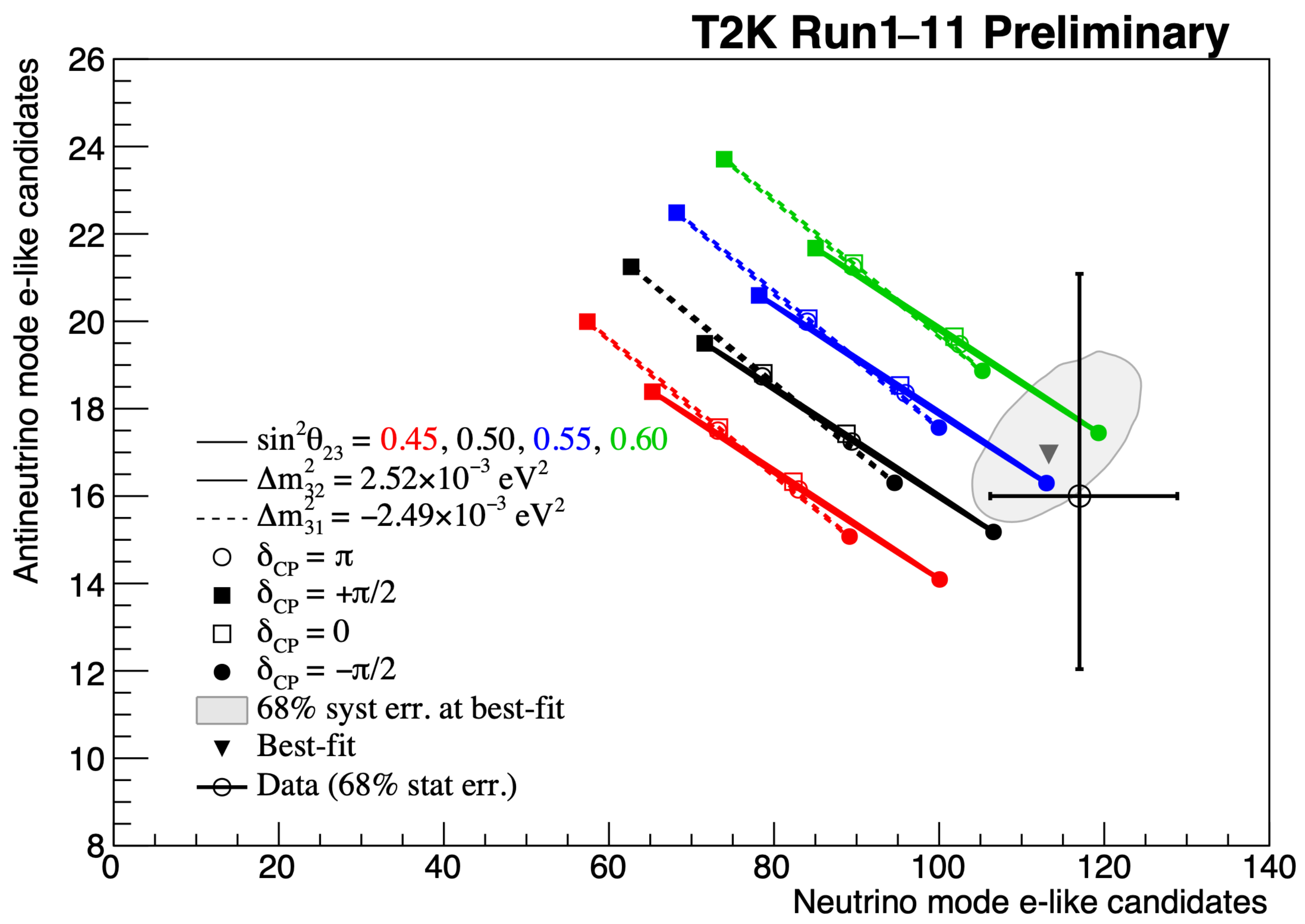
ND280-upgrade

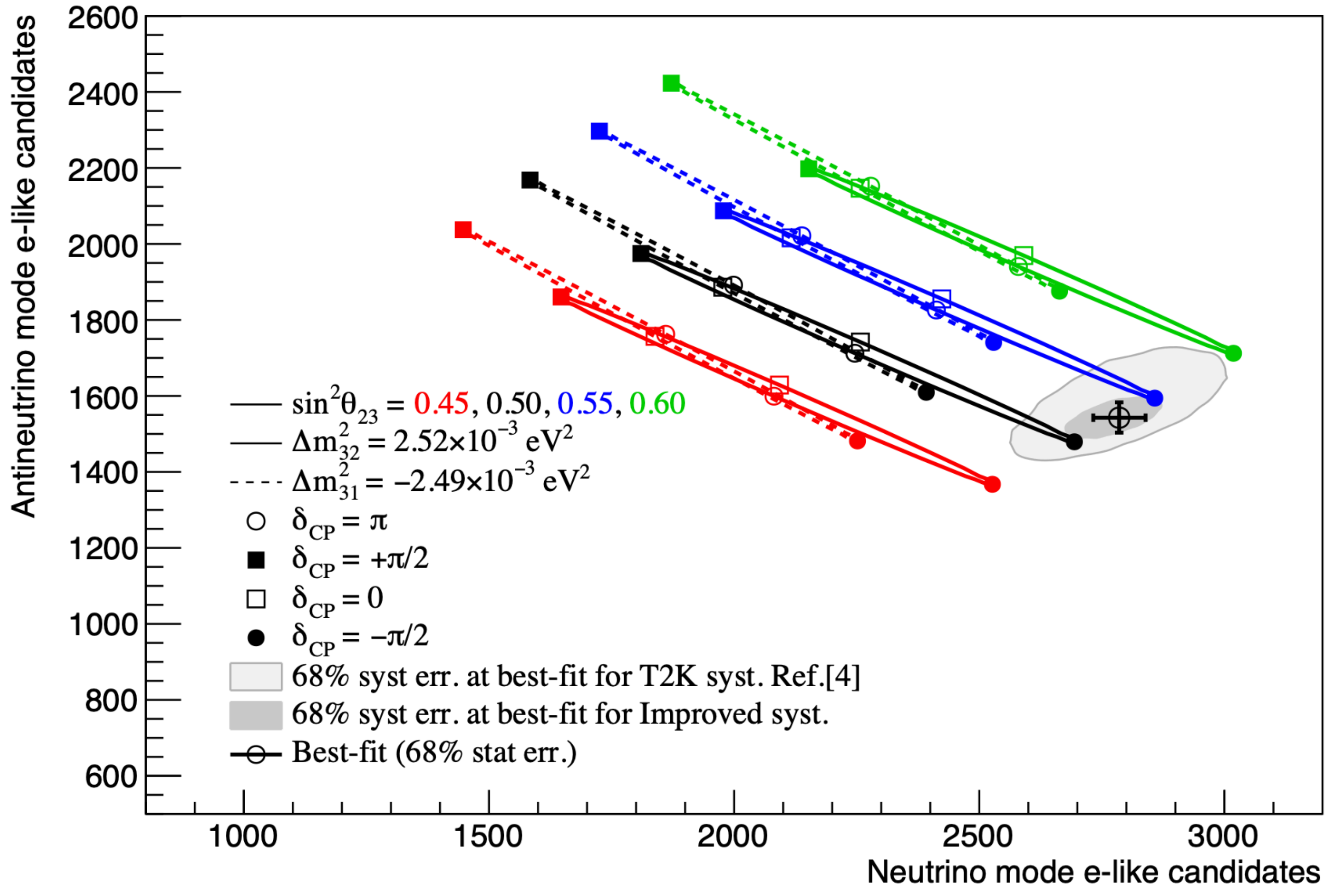
Hyper-Kamiokande



From T2K to HK

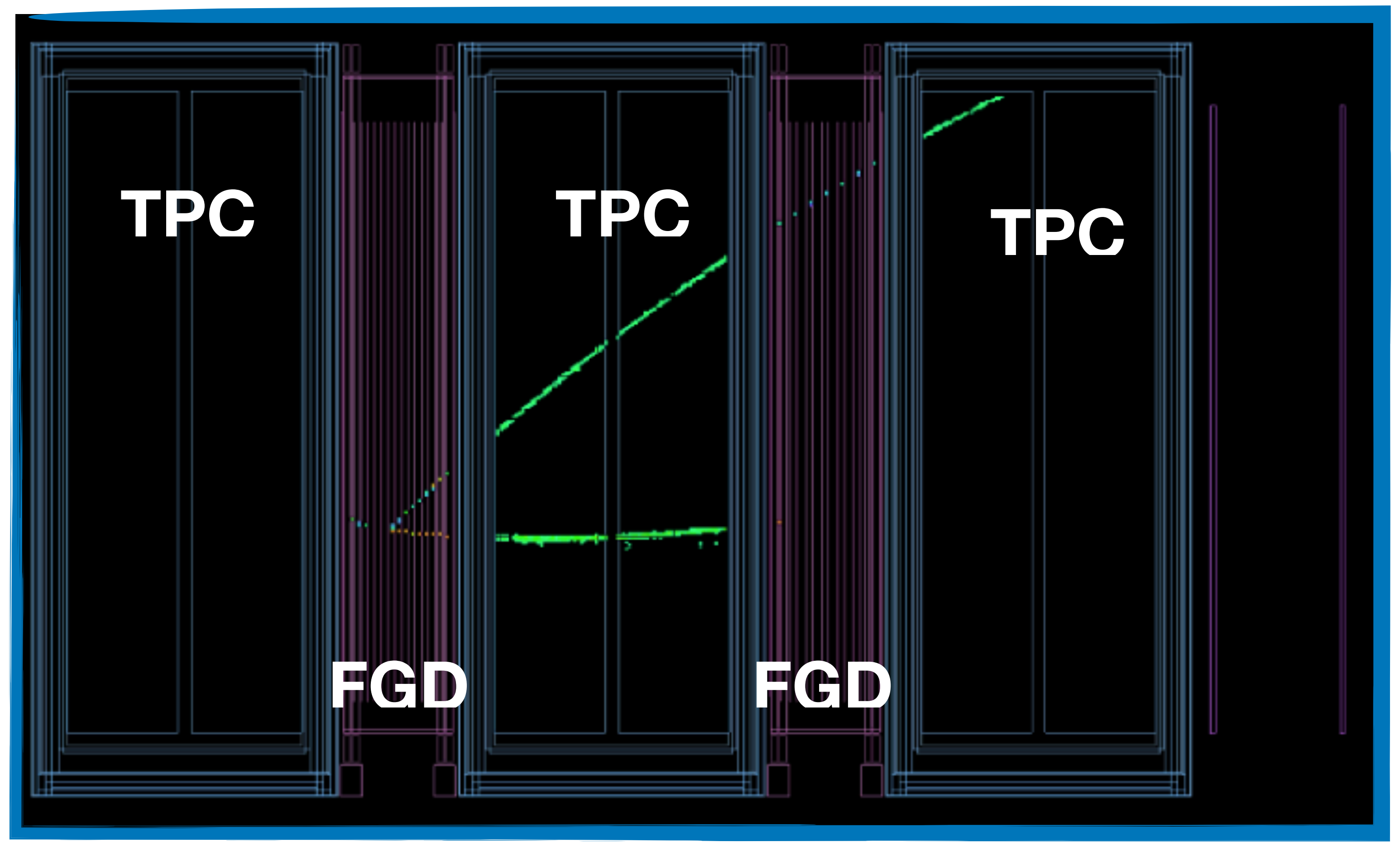




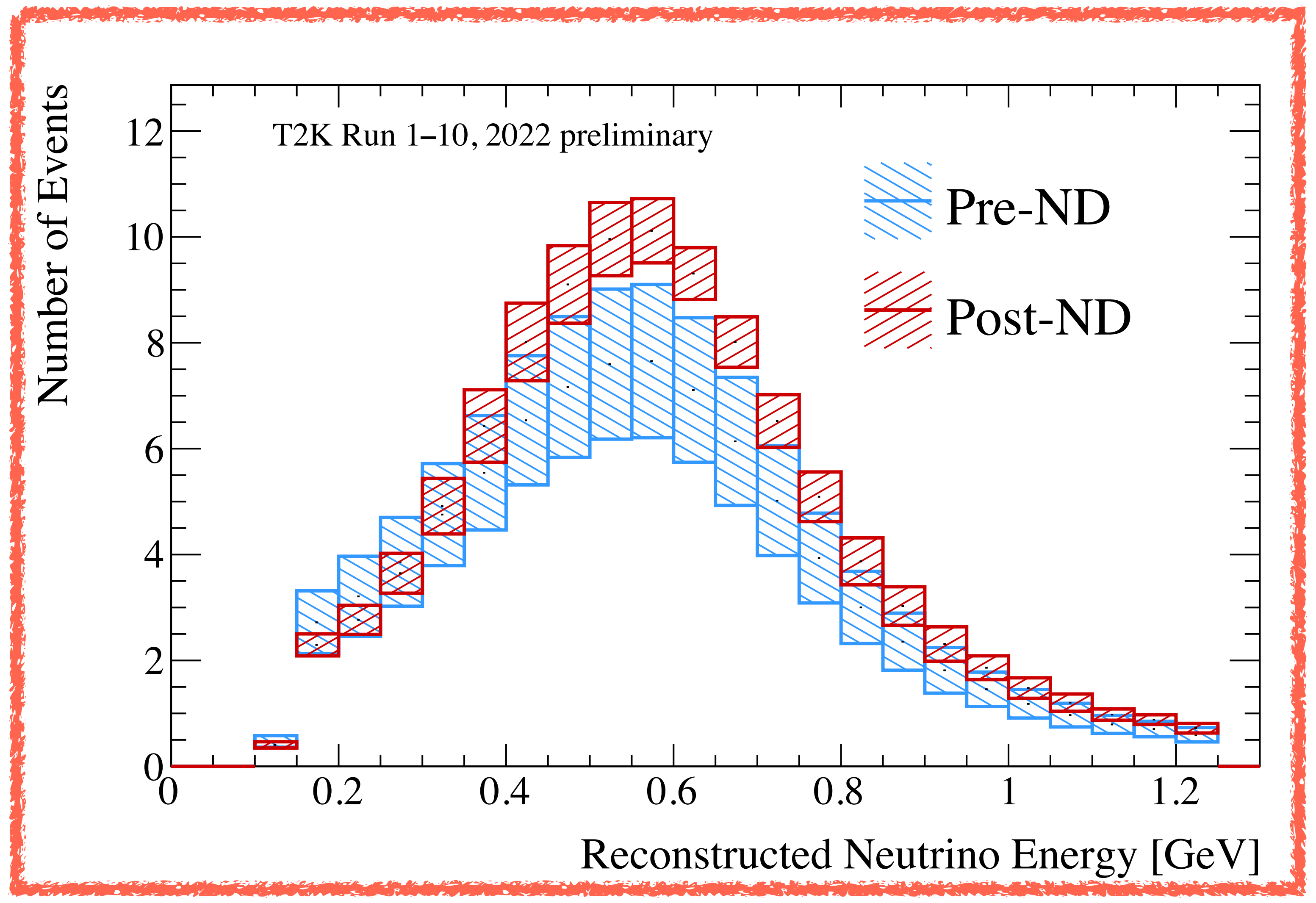


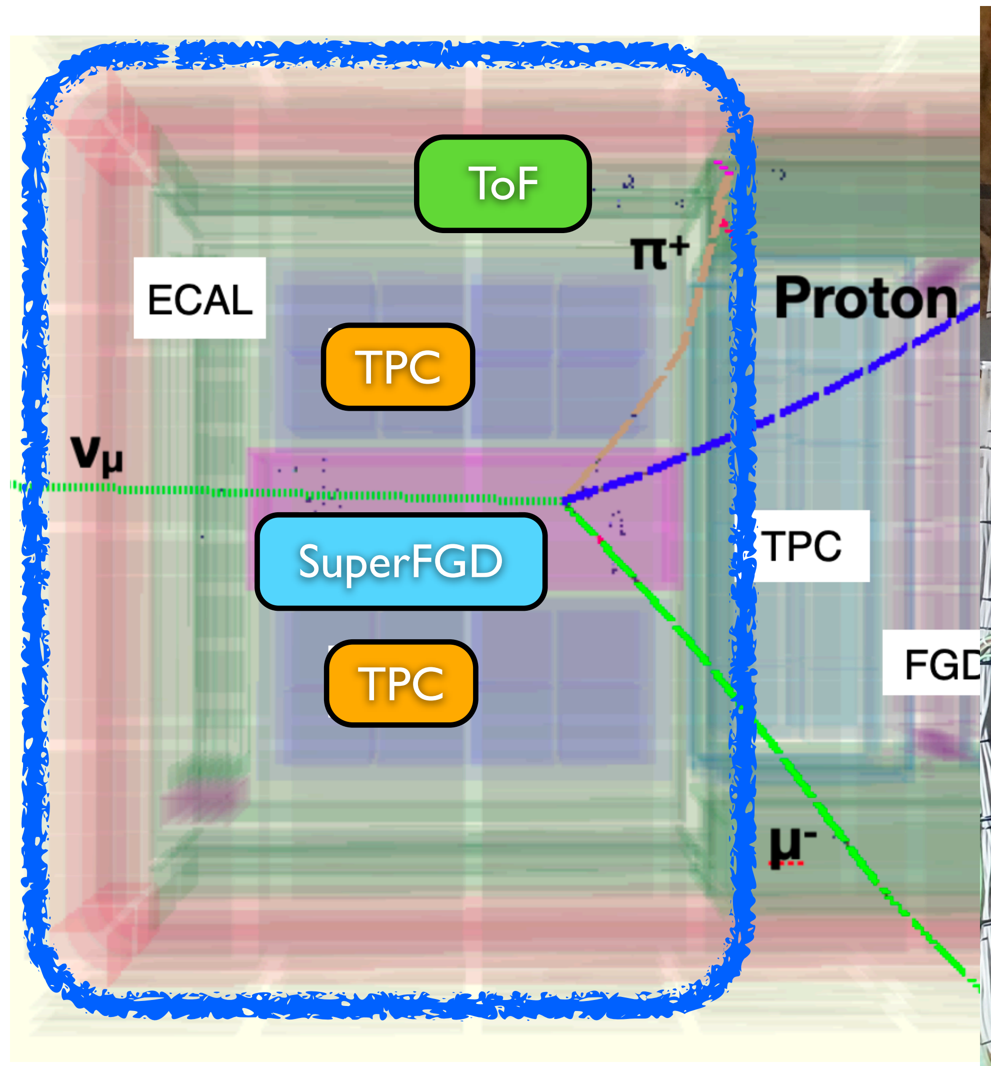
- CPV in leptonic sector → difference in $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \nu_e)$
- T2K observed first hints of CP violation hints based on <150 appearance events
- HK will collect > 2000 events of ν_e and $\bar{\nu}_e$ appearance
- Need to reduce systematics with Near Detector data

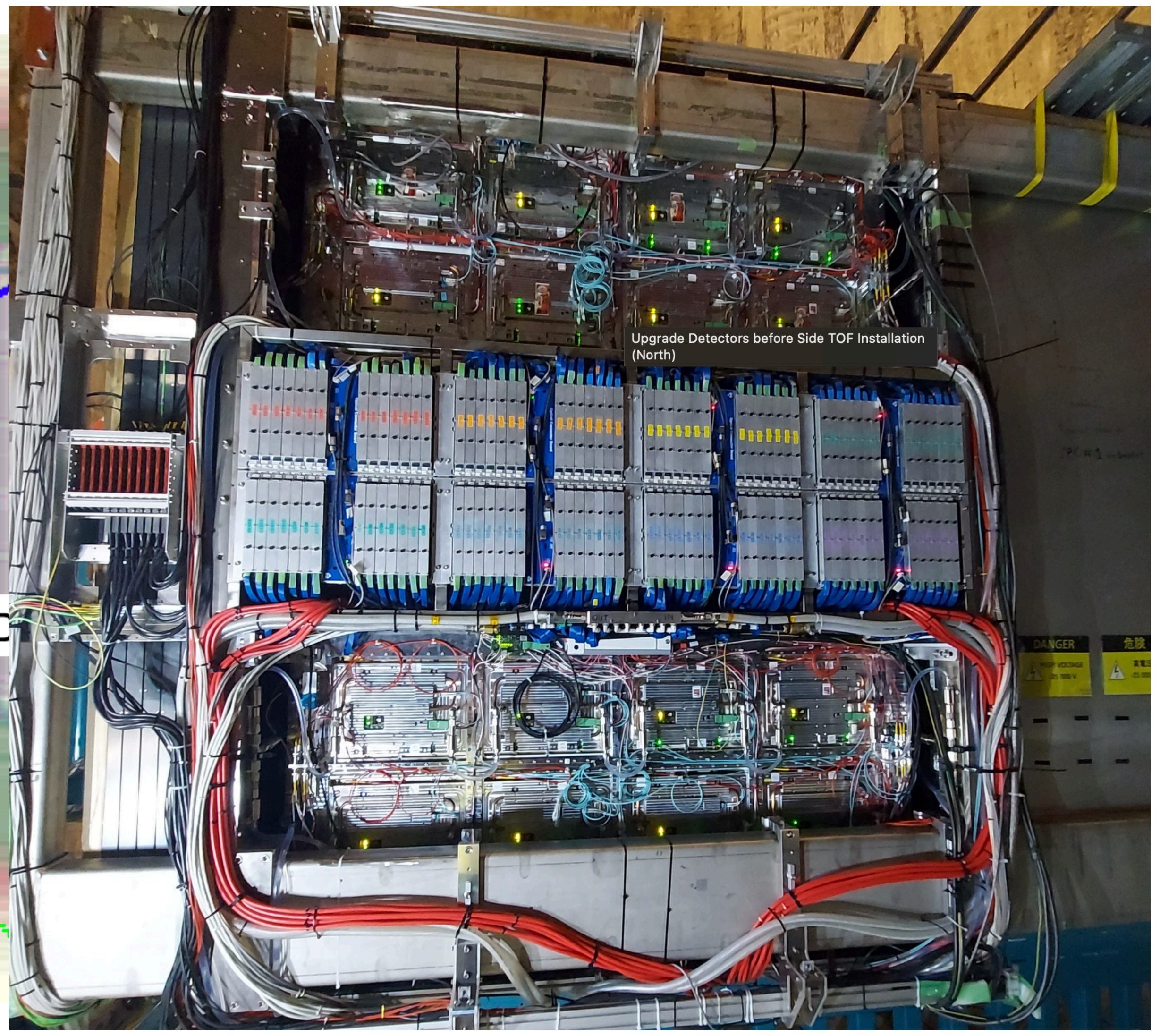
T2K ND280 upgrade



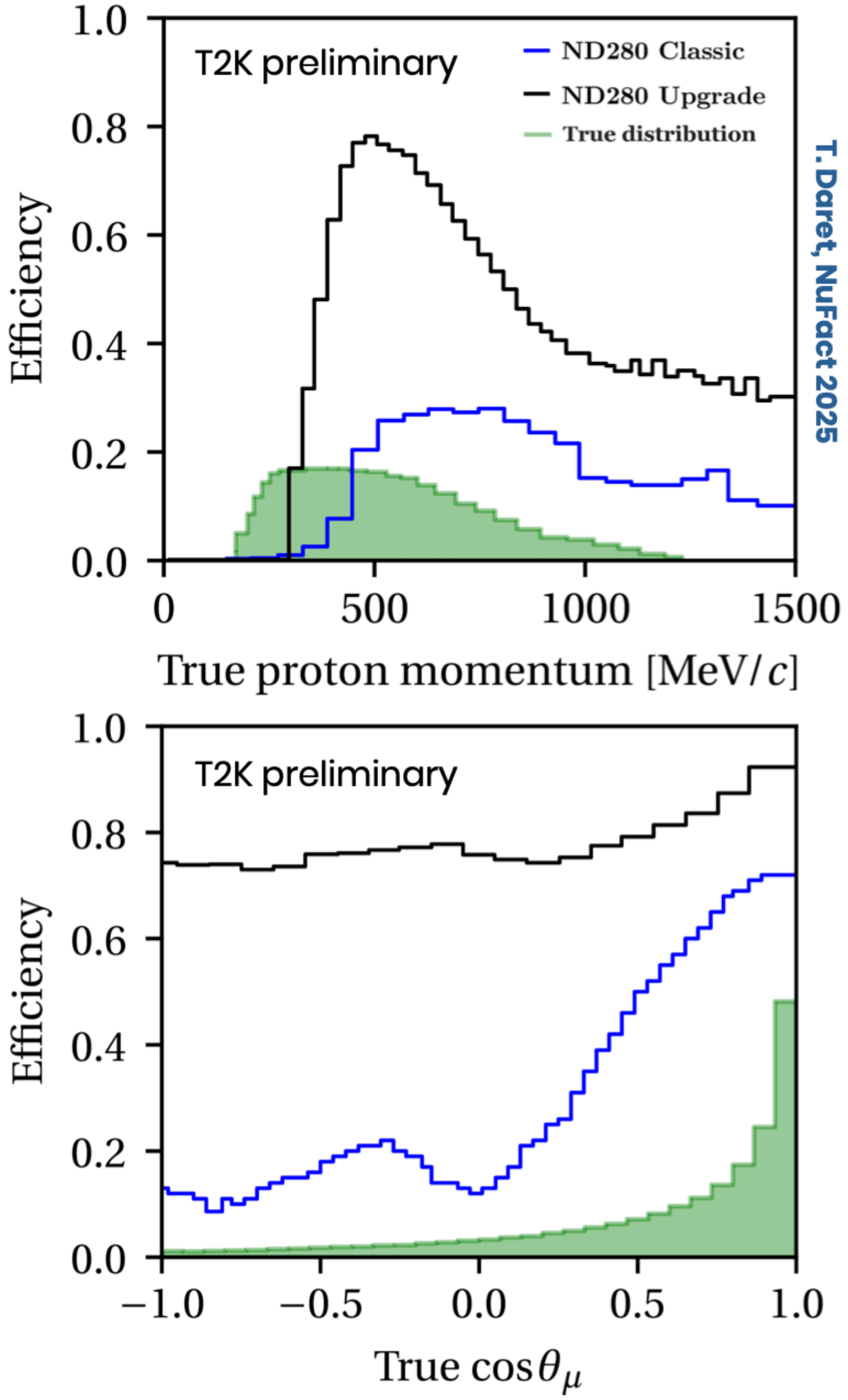
SK single ring e-like sample





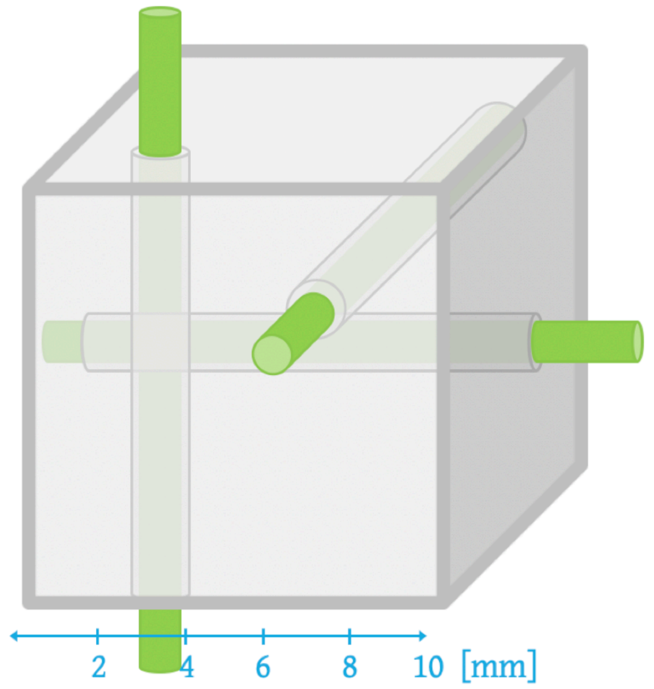


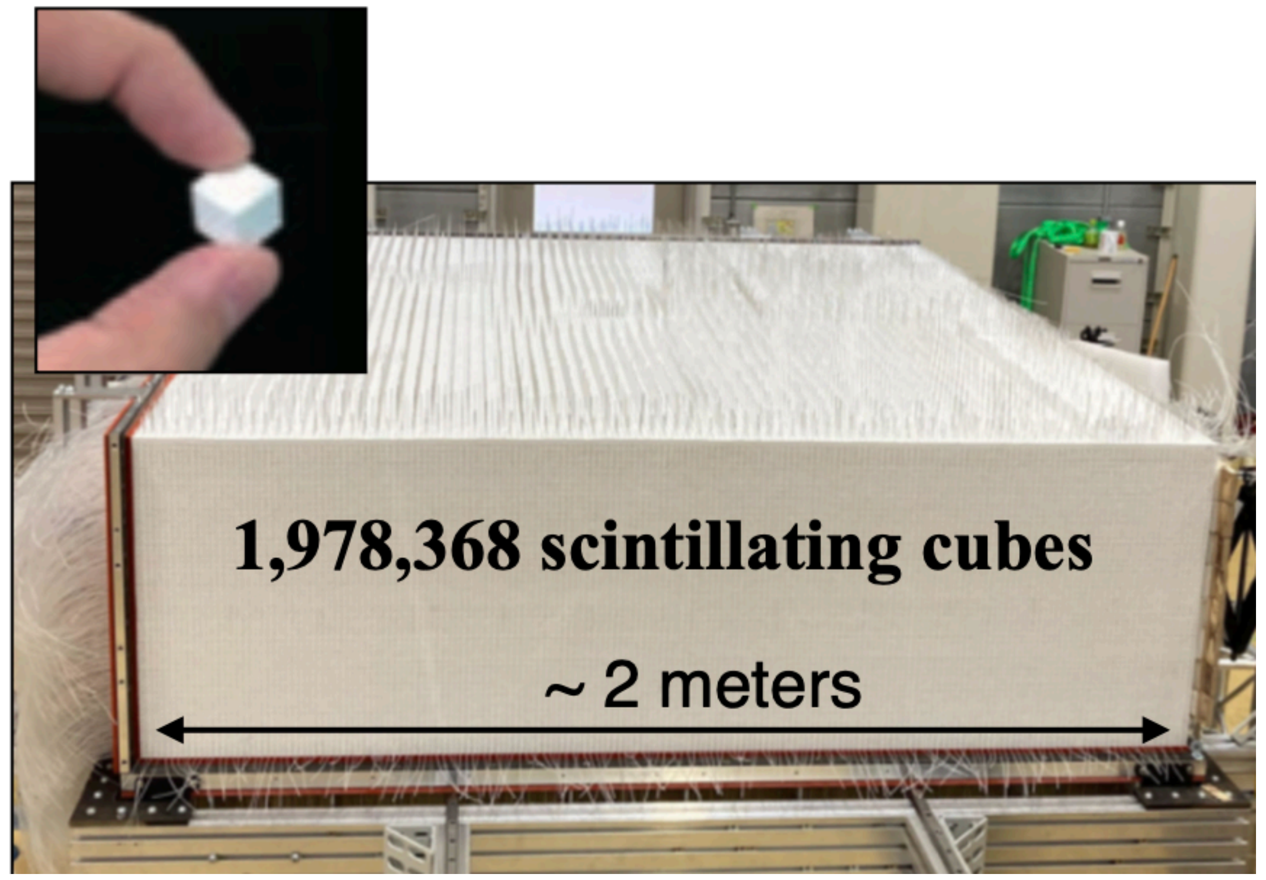
Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two TPCs and a ToF detector



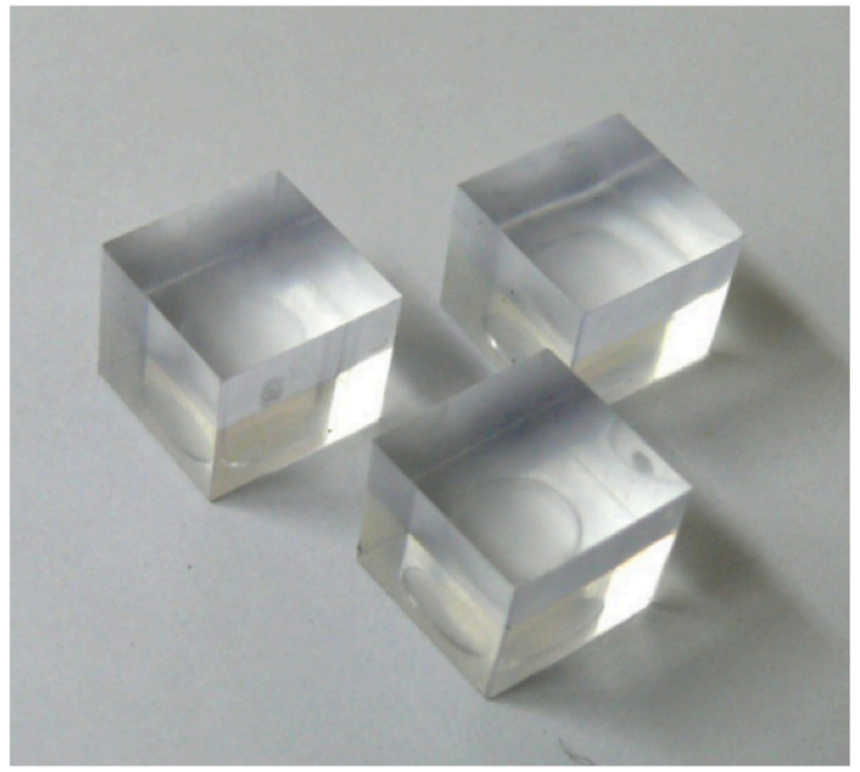
T.Daret, NuFact 2025

Super-FGD detector

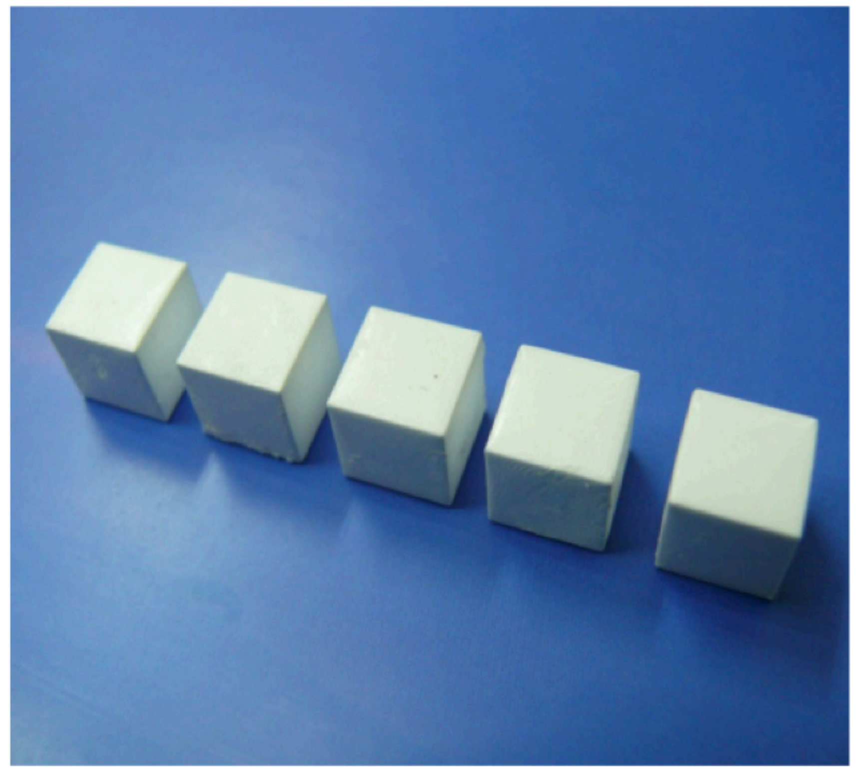




Produce cubes by injection molding

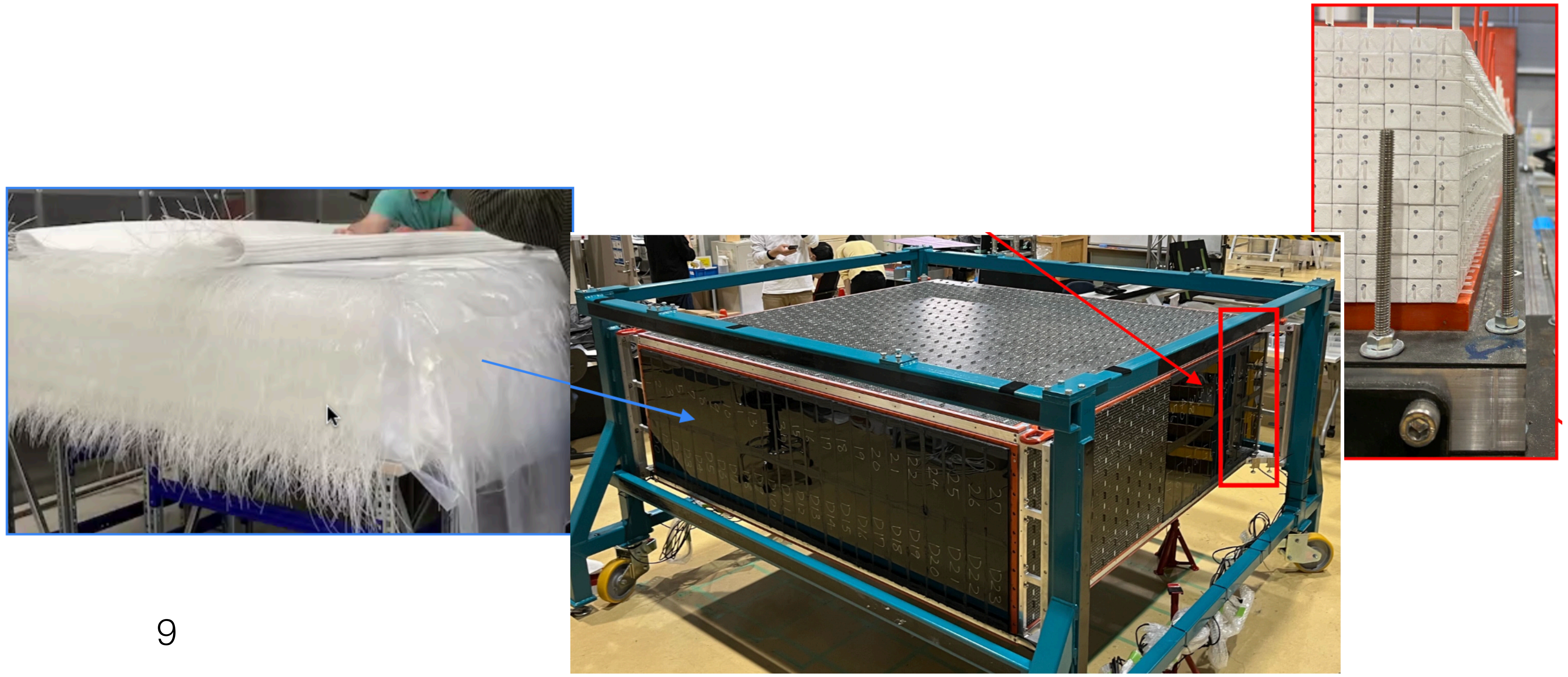


Etched in a chemical to deposit a reflective layer



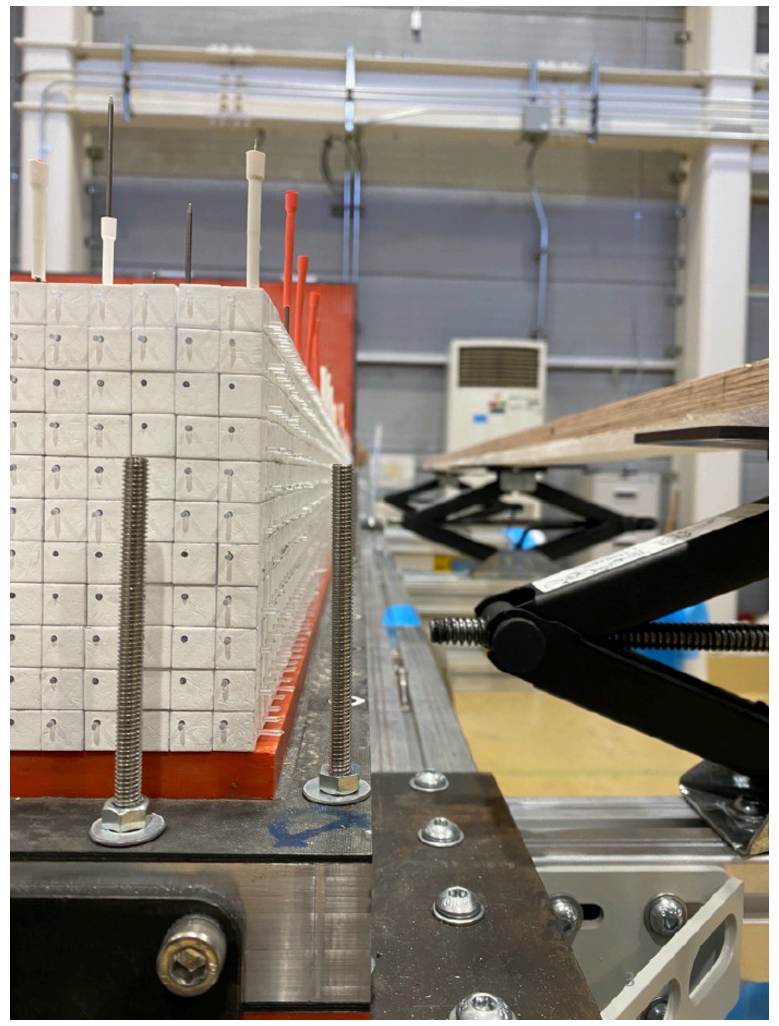
3 orthogonal holes are drilled

- 2 millions optically independent plastic scintillator cubes
- Each crossed by 3 WLS → 3D readout
- 60k SiPM + electronics channels

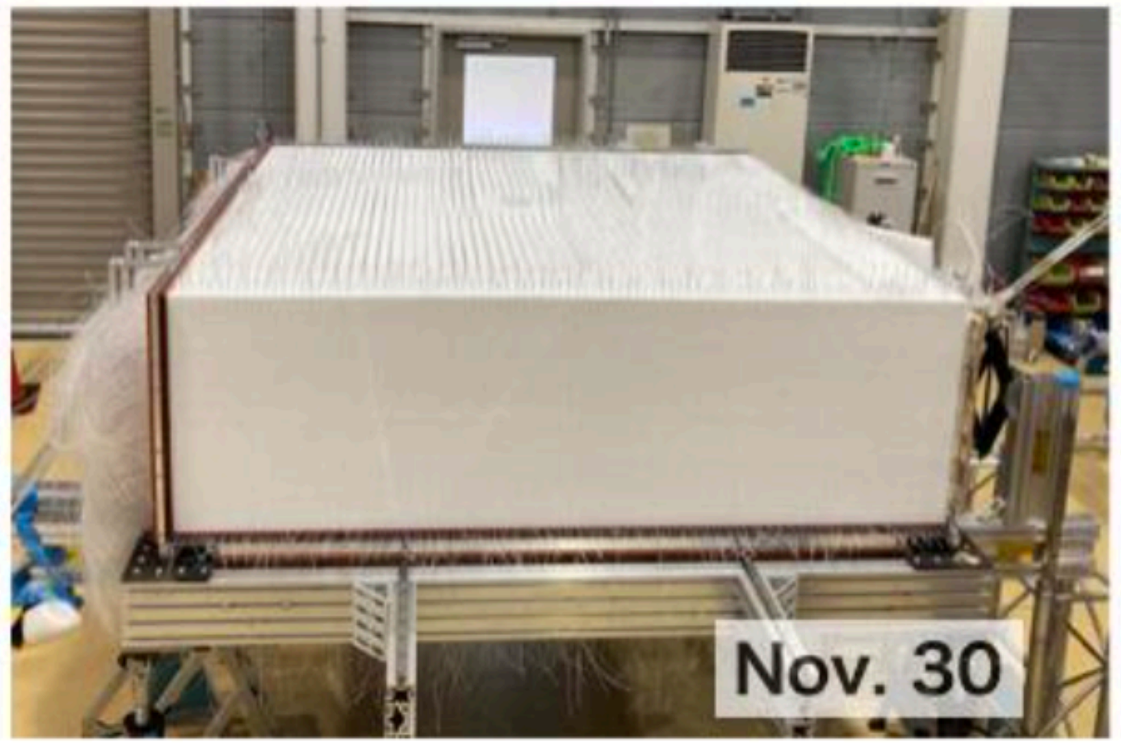


SuperFGD assembly at J-PARC (2023)

First cube layer assembly



Stop panels removed

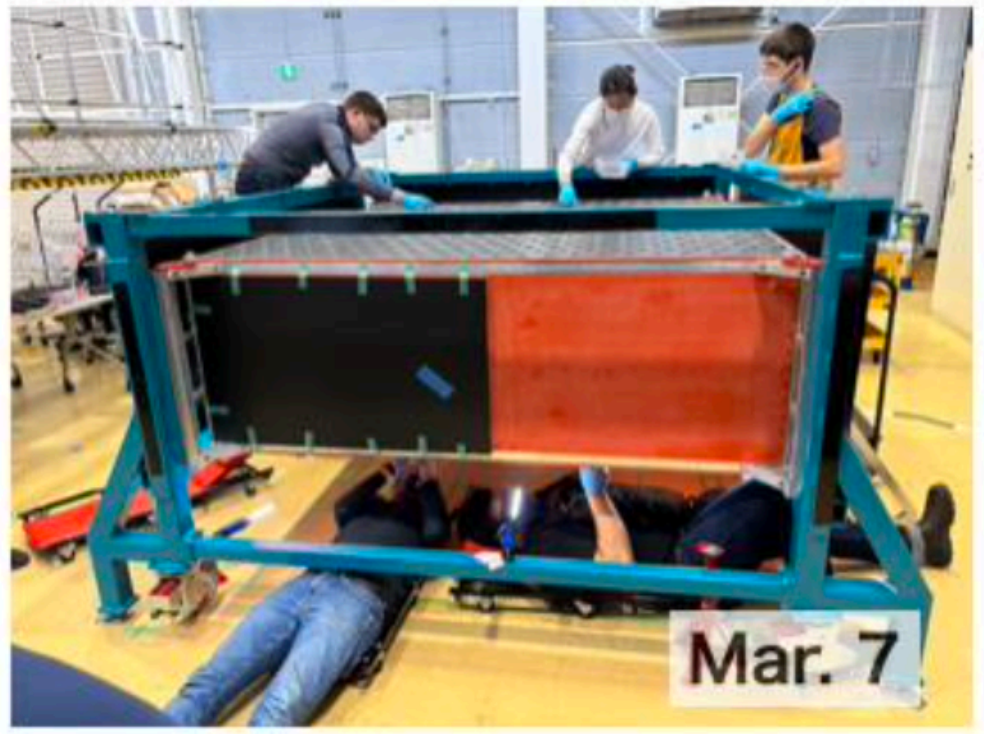


Box closure

Horizontal fibers assembly

Vertical fibers assembly

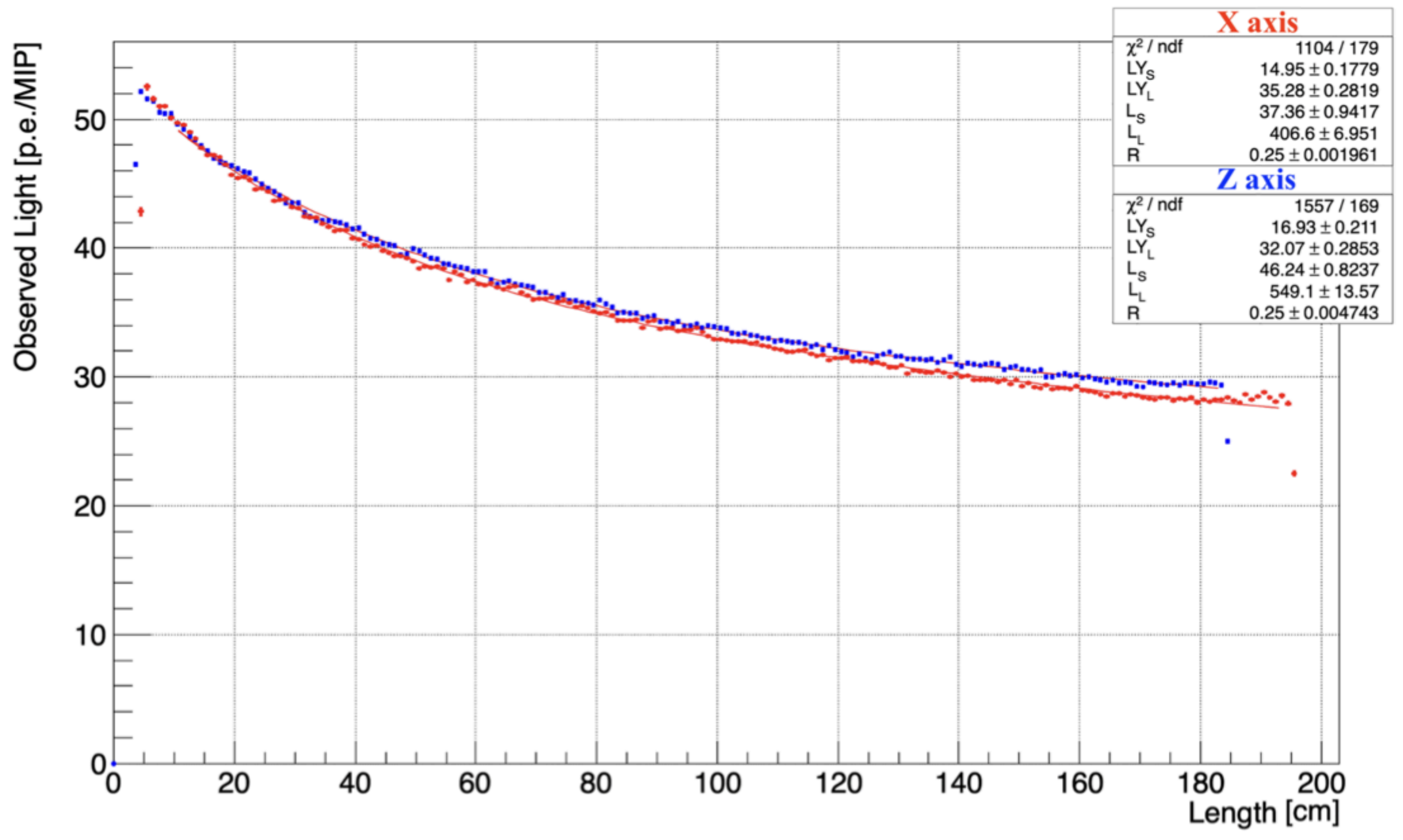
Top MPPCs assembly

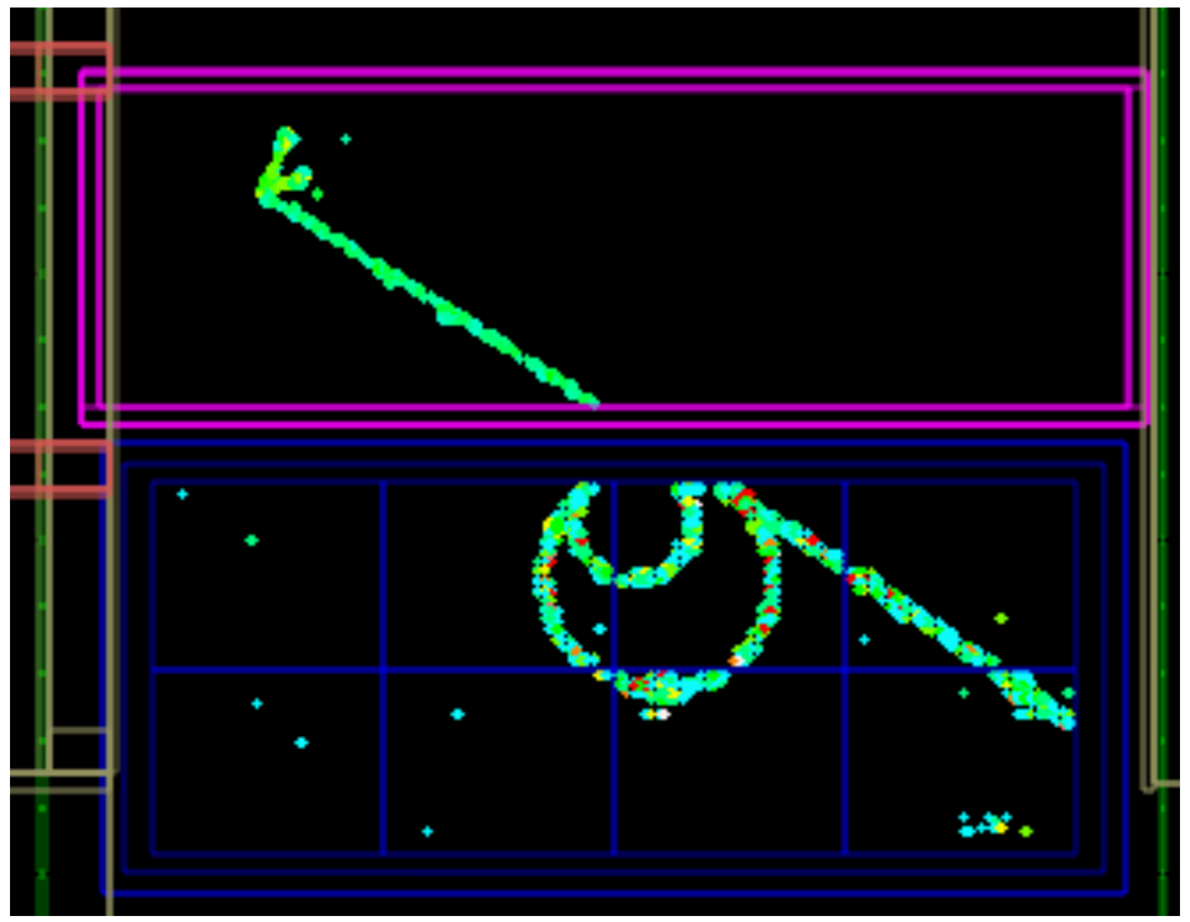


Light barrier/cables asse

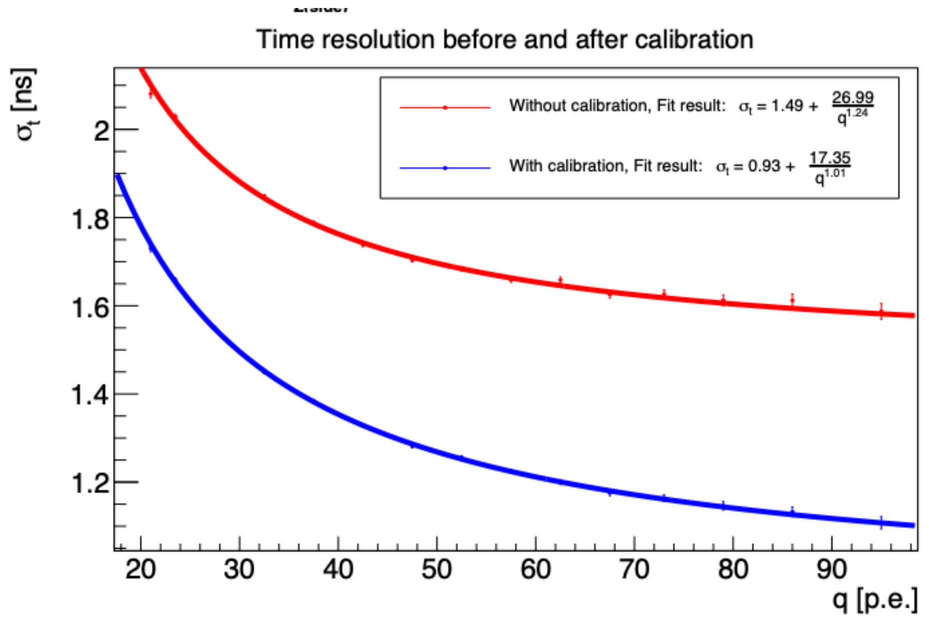
Super-FGD performances

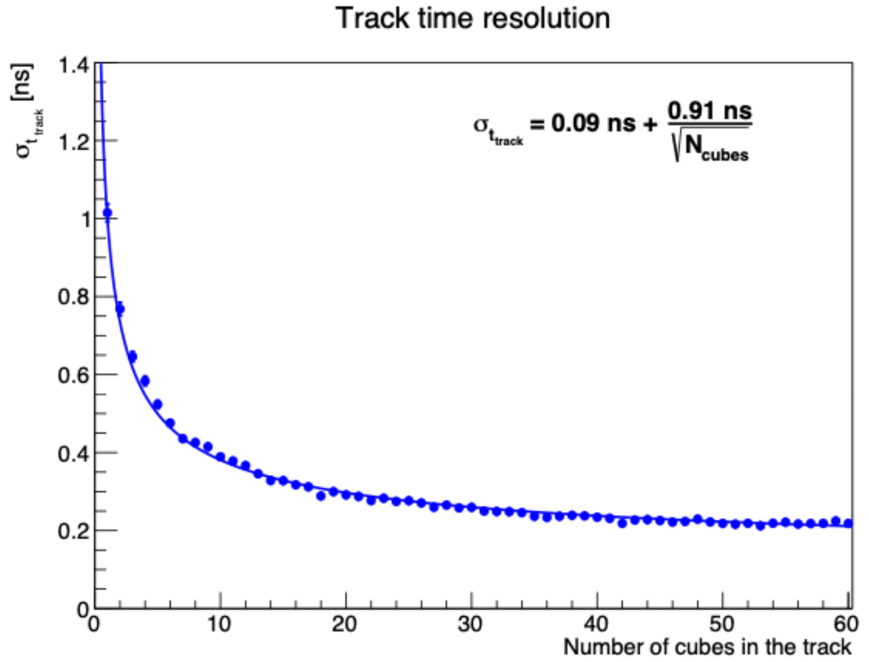
LY of 50 p.e per fiber per MIP (decrease with distance from MPPCs)

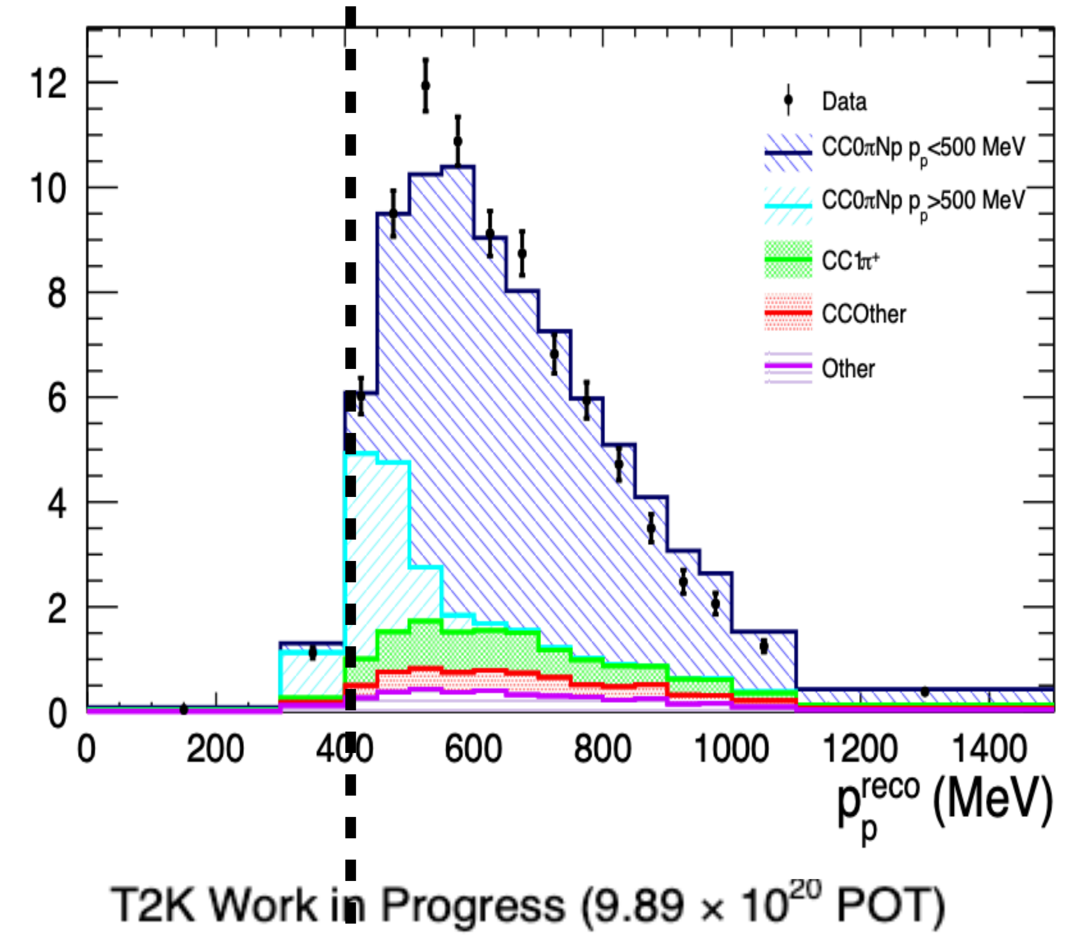




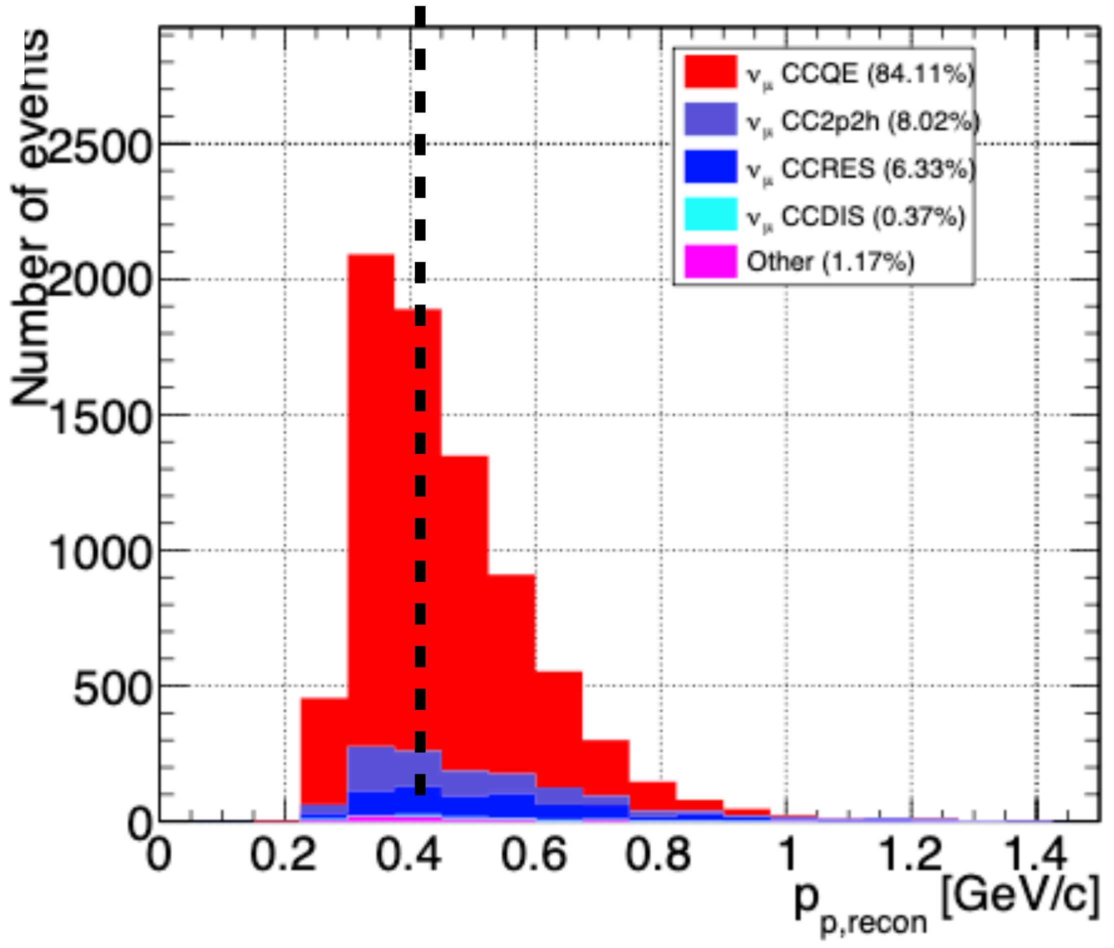
Time resolution ~ 1.2 ns per cube



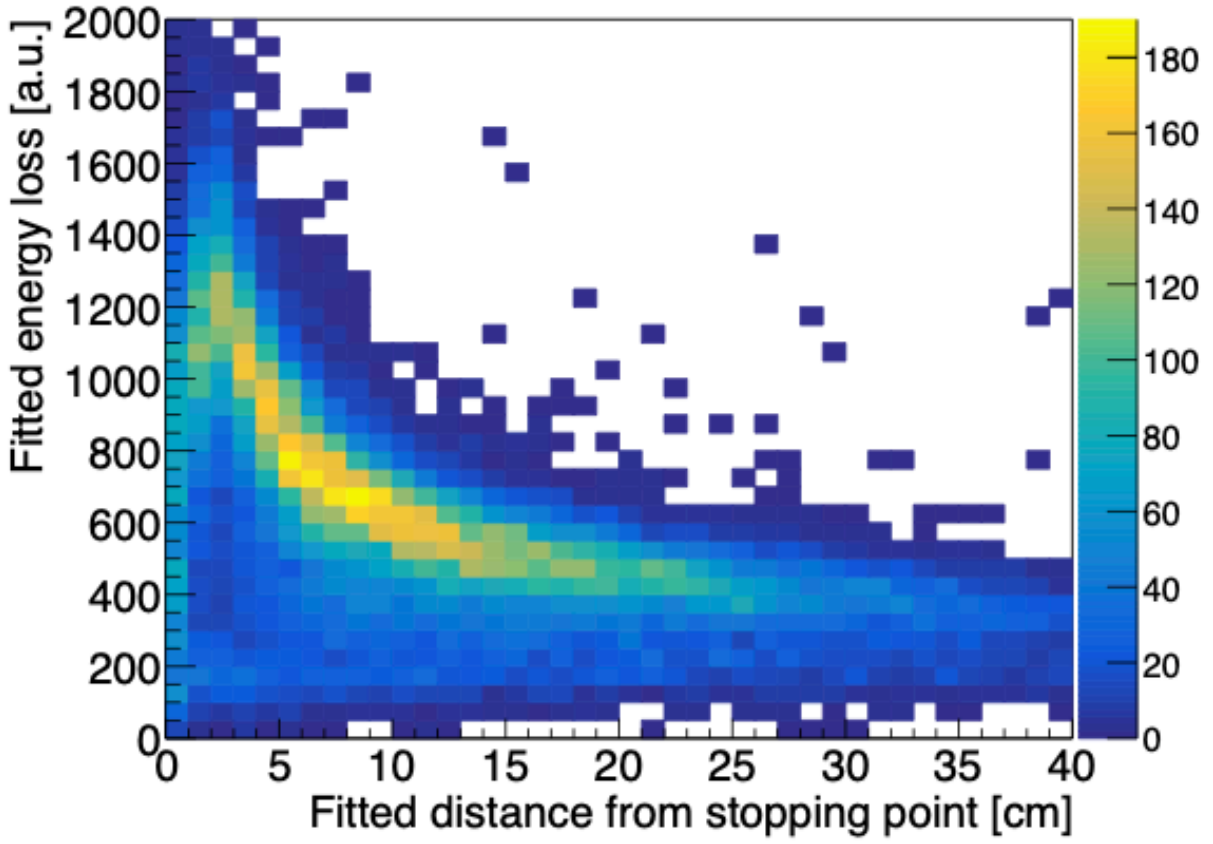




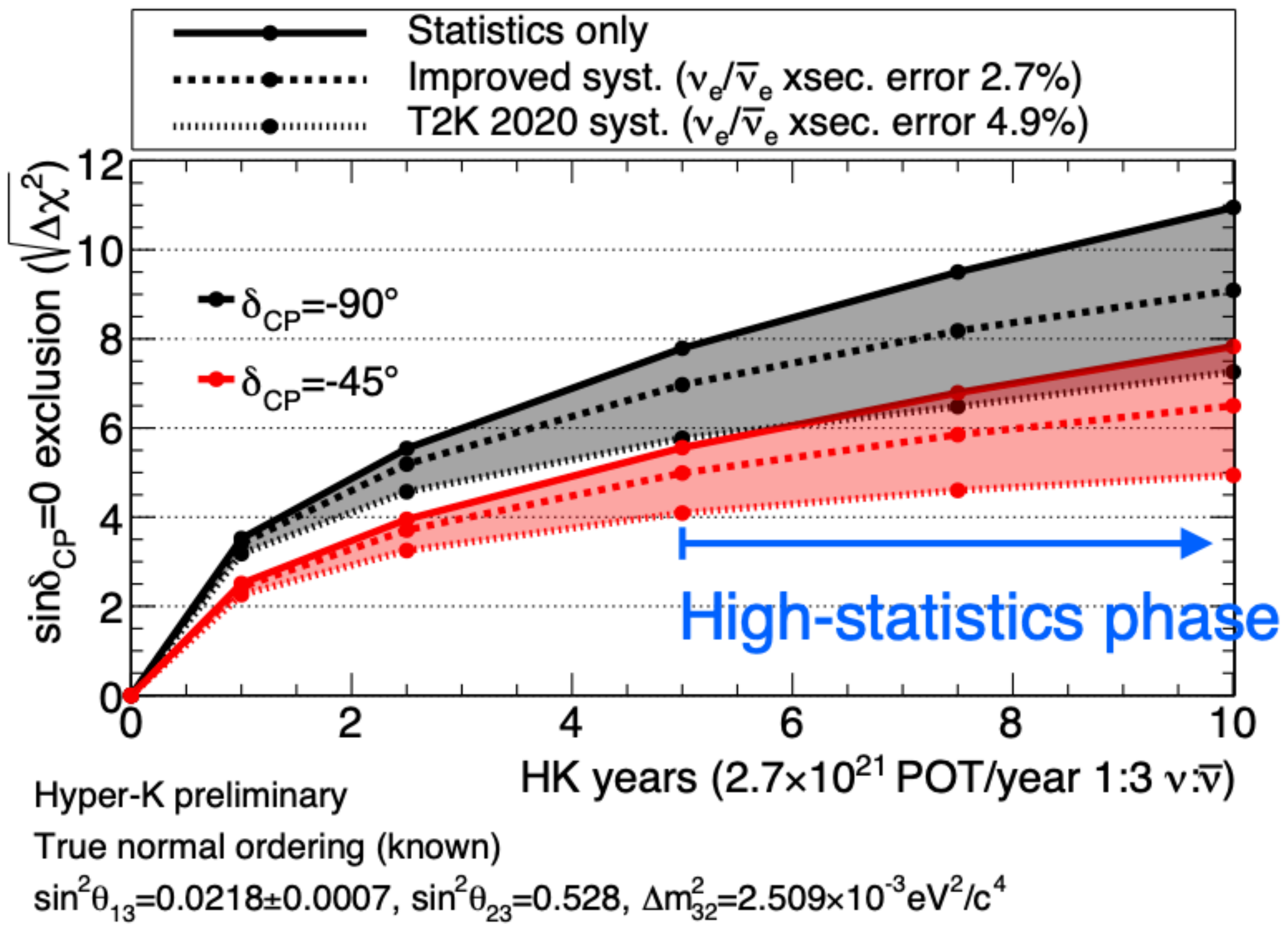
sFGD

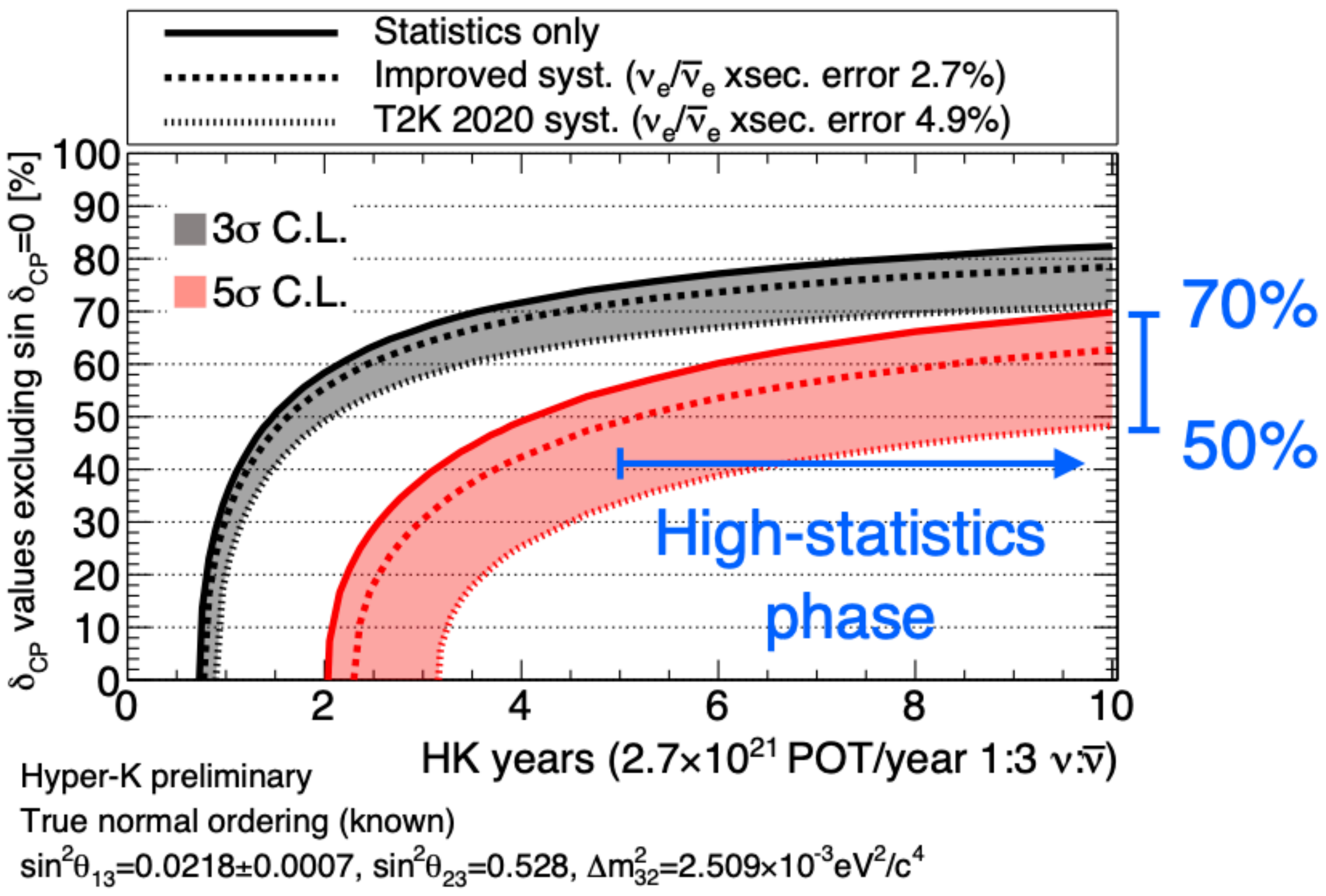


Protons Bragg peak



Hyper-K sensitivity

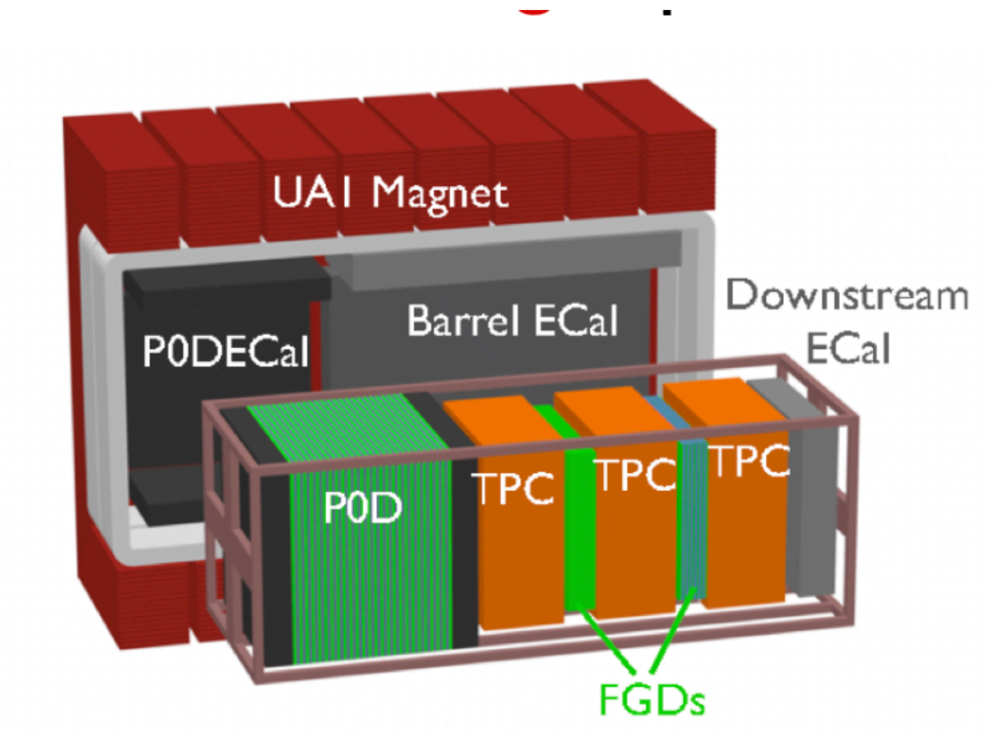




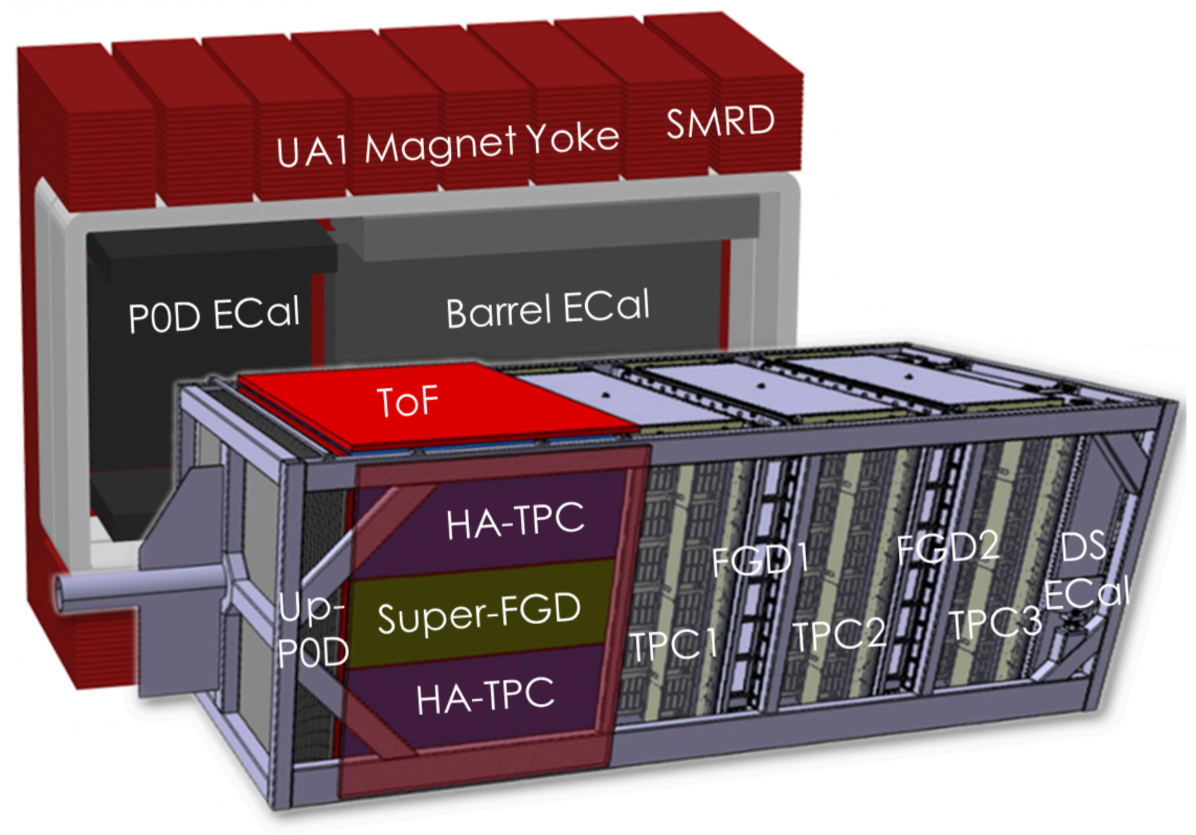
- HK will quickly measure CPV if δCP is large
- If δ_{CP} is small and if we want to make a precision measurement we will be quickly limited by systematics uncertainties → need better constraints from ND280!

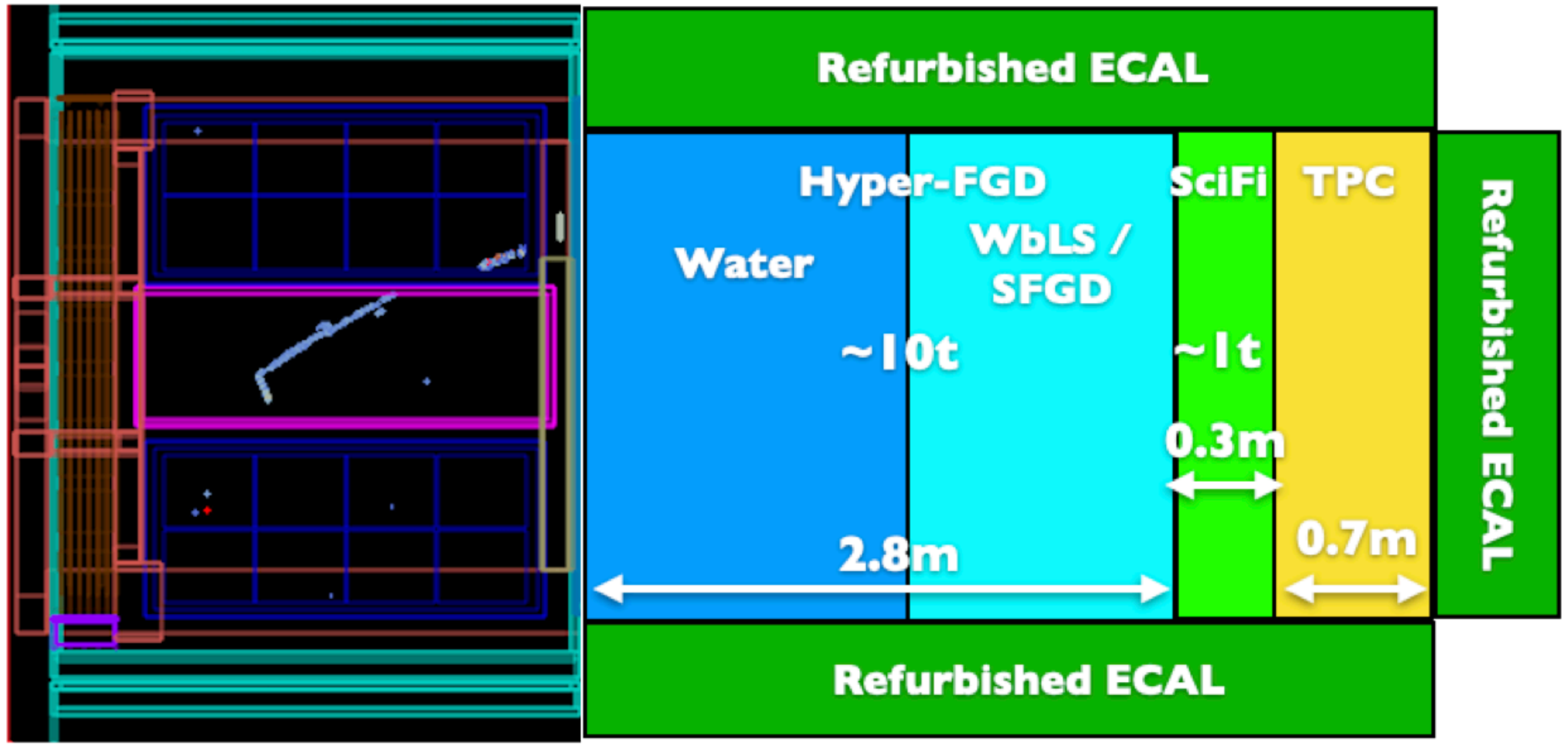
ND280++

- Still profit of ND280 magnetised detector to distinguish ν from $\bar{\nu}$
- Modular detector → can be upgraded in steps
- Recently upgraded with a new 2t high granularity target (Super-FGD)
- A second upgrade will be done during HK to replace the tracker region → ~10 ton available for new ideas!
- Active R&D is on-going
- ANR PRCI project LPNHE/ETHZ on water based Liquid Scintillator
    - Collaboration with BNL (WbLS inventors) and Kyoto groups

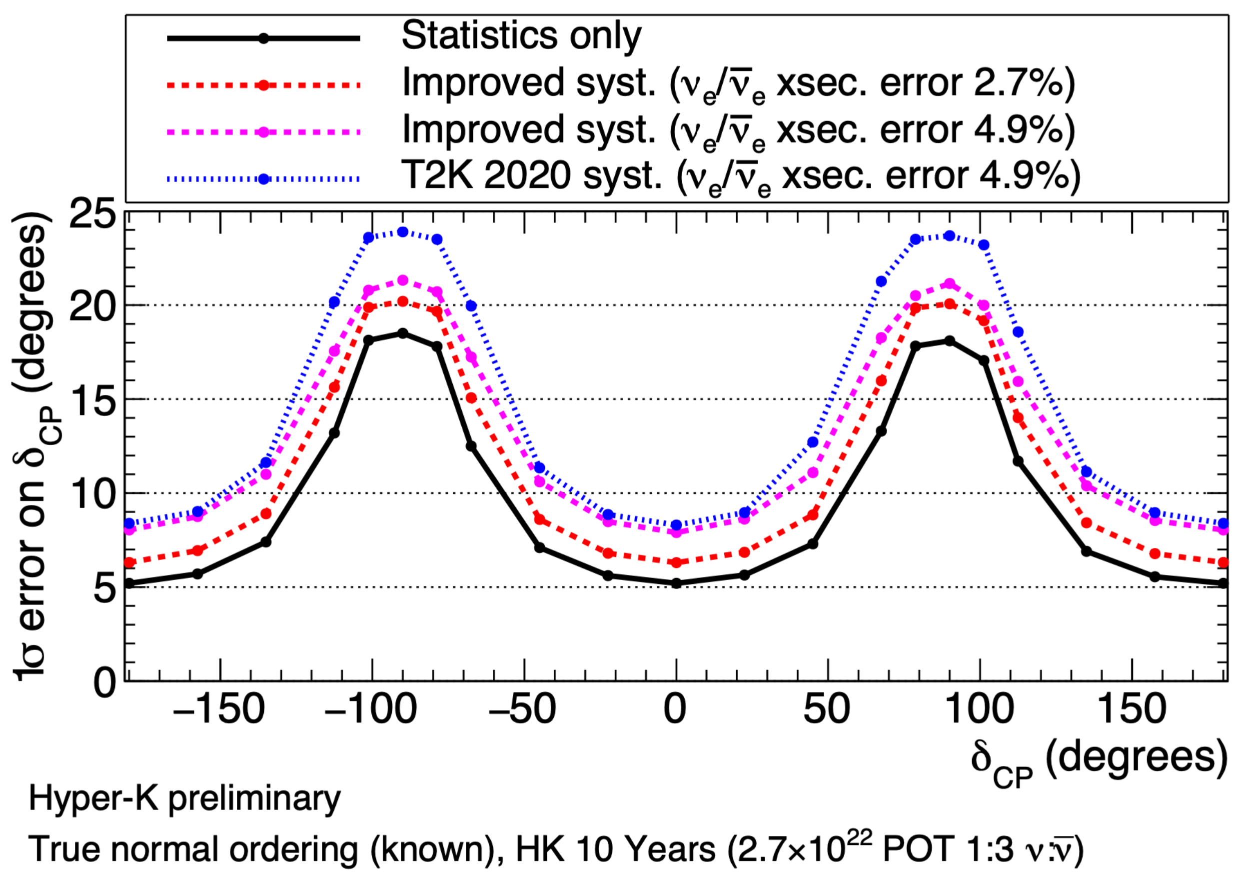


Old ND280



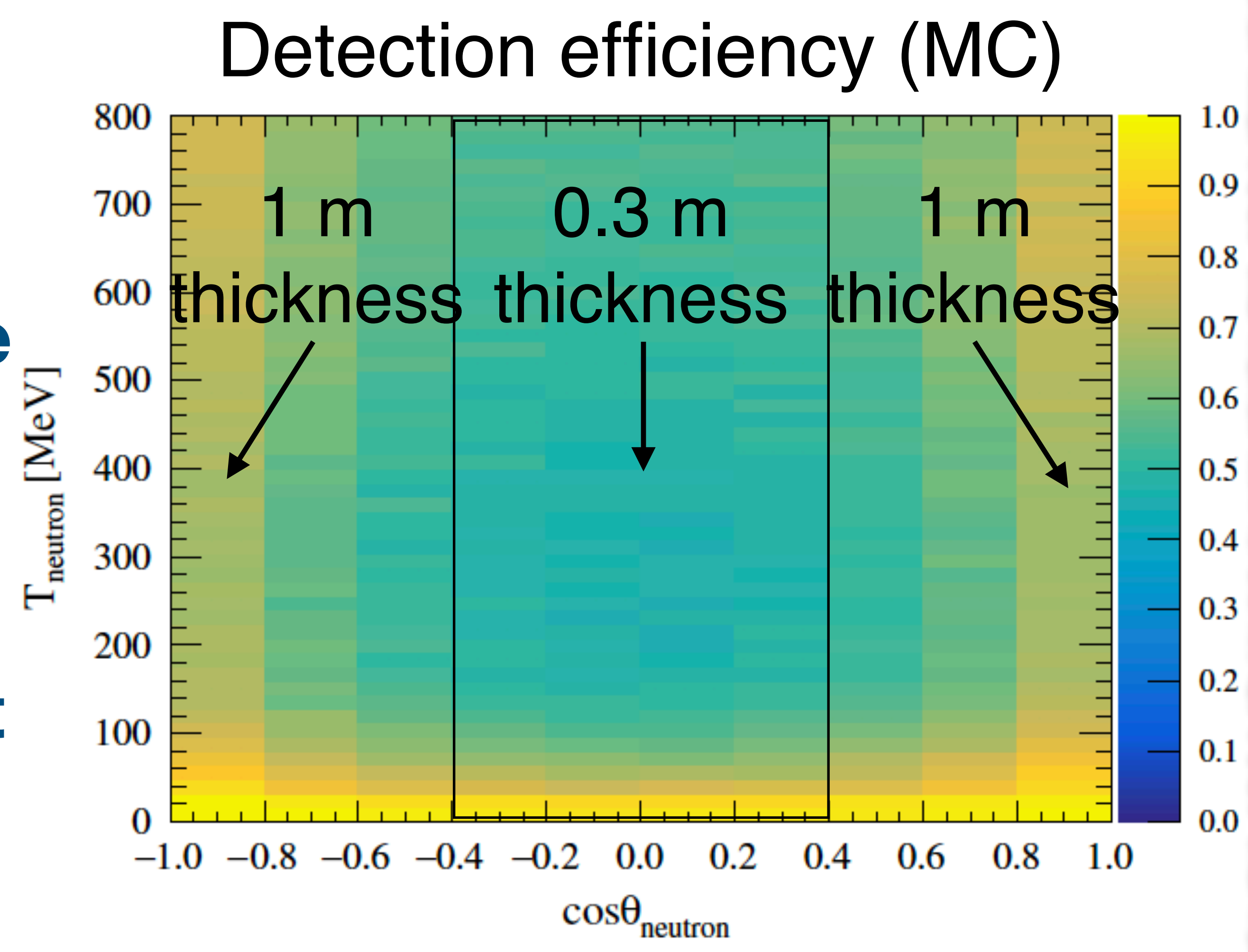


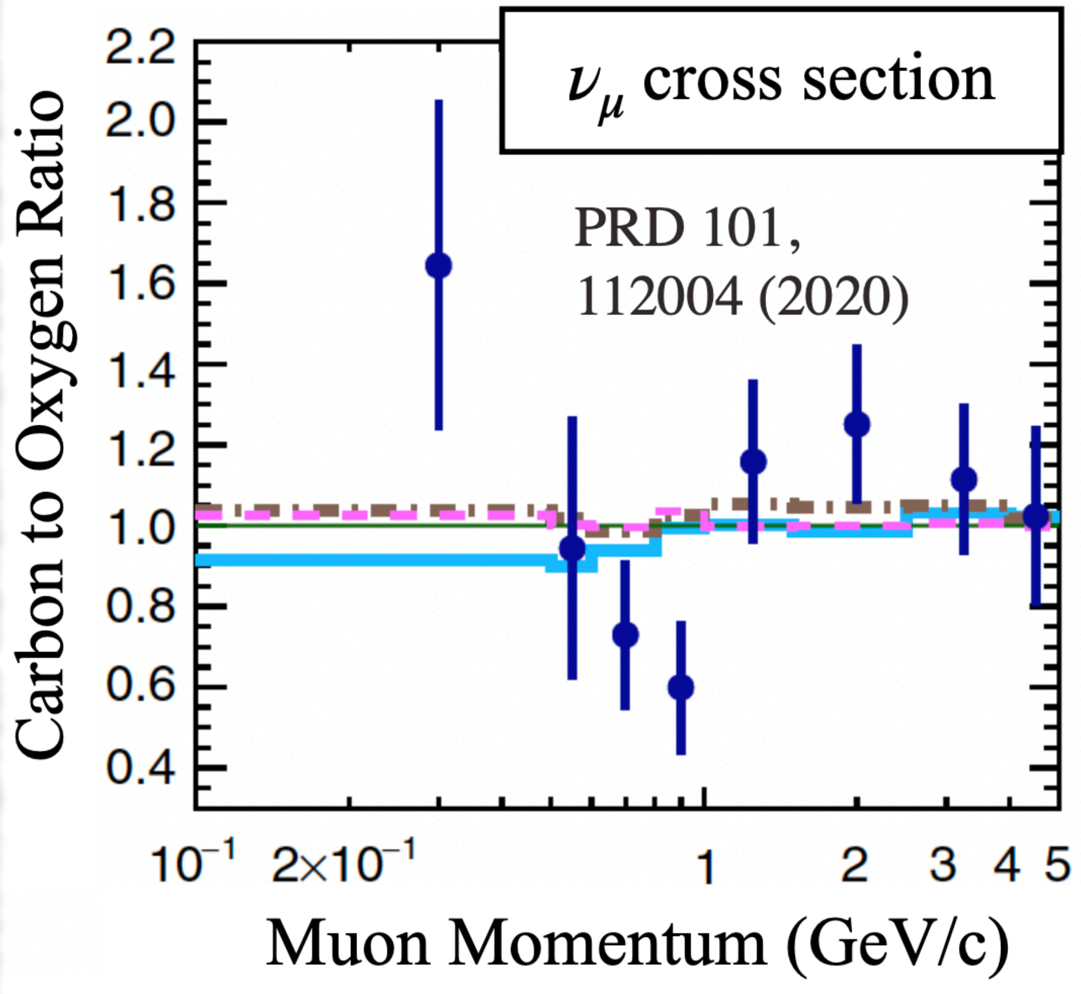
ND280 challenges for HK



Ultimate precision measurement of δ_{CP} dominated by ν_e/ $\bar{\nu}_e$ uncertainties → measure them with higher statistics at the Near Detector

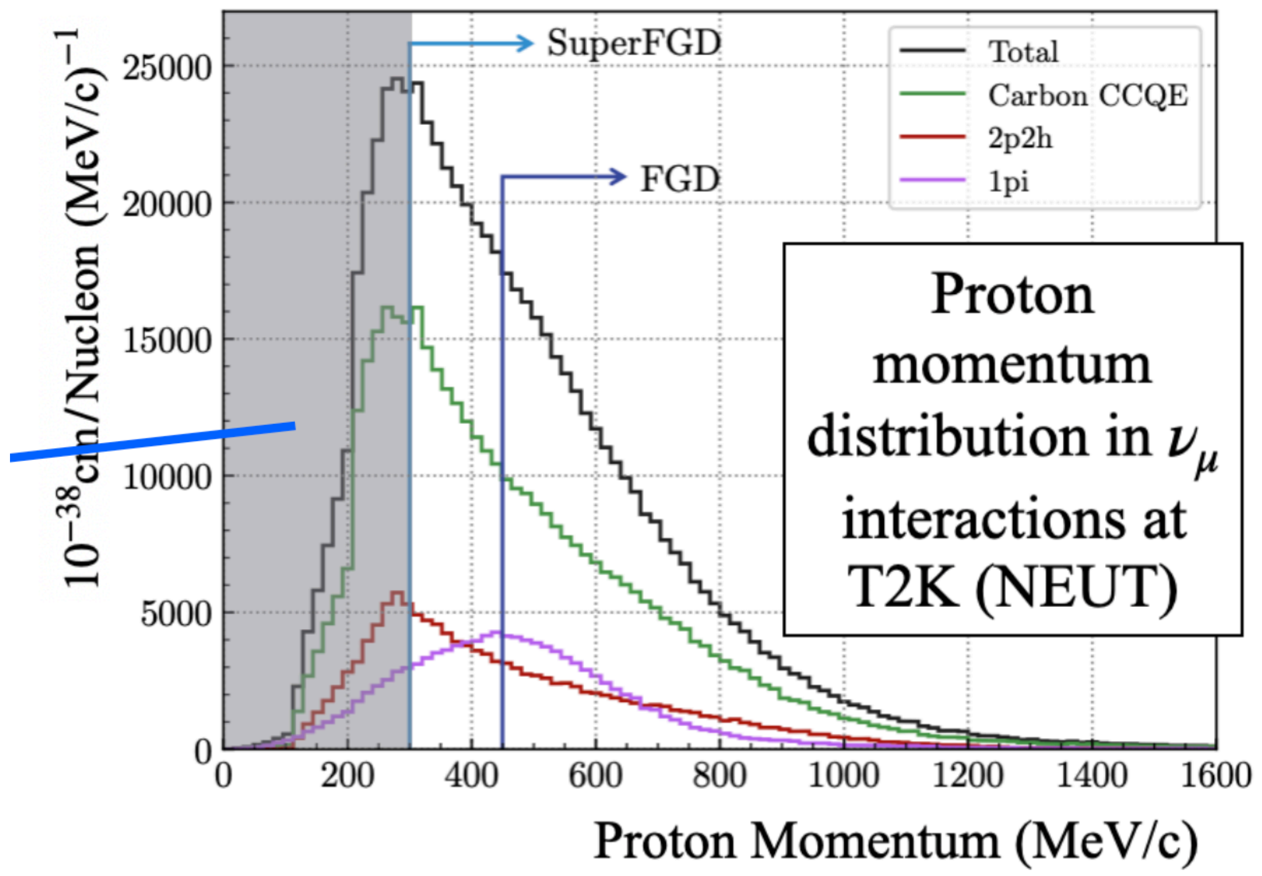
For $\bar{\nu}$ interactions it is crucial to measure neutron kinematics → many neutrons escape from sFGD → build larger target



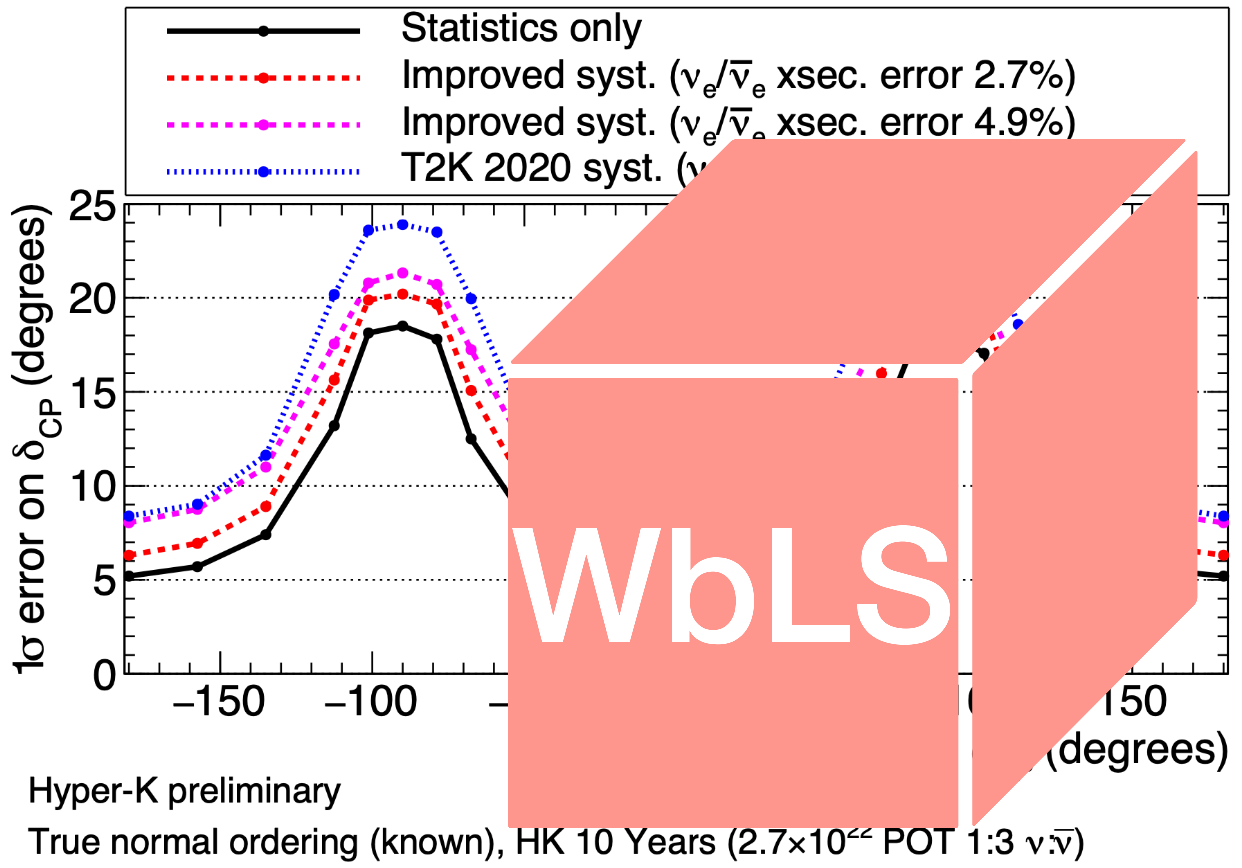


Scaling of cross-section model from Carbon (ND280) to Oxygen (SK/HK) also bring some additional uncertainties → add Water in ND280

For short protons tracks sFGD granularity is not enough and we still miss ~half of the protons → build target with larger granularity



ND280 challenges for HK



Ultimate precision measurement of δ_{CP} dominated by ν_e/ $\bar{\nu}_e$ uncertainties → measure them with higher statistics at the Near Detector

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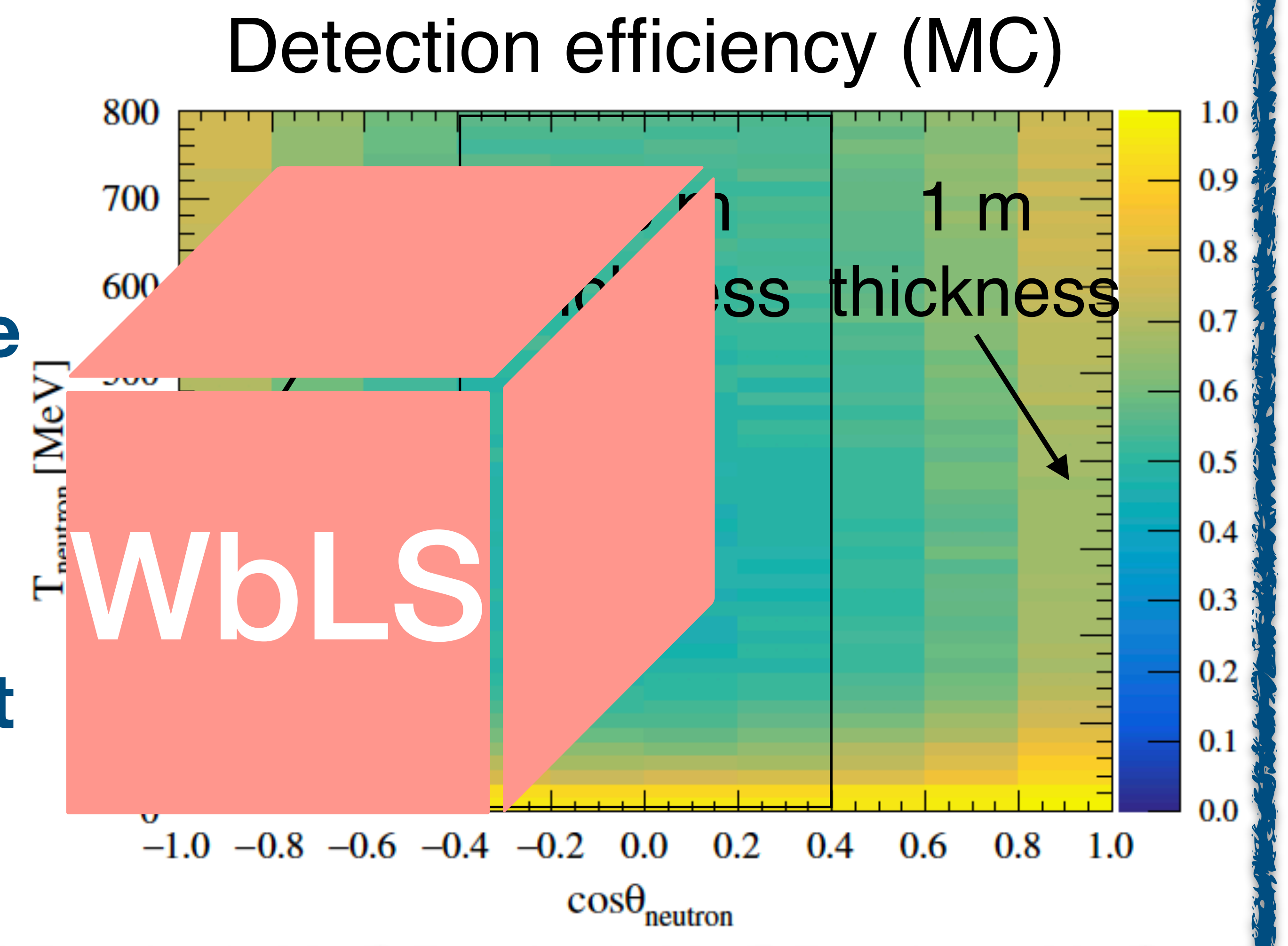

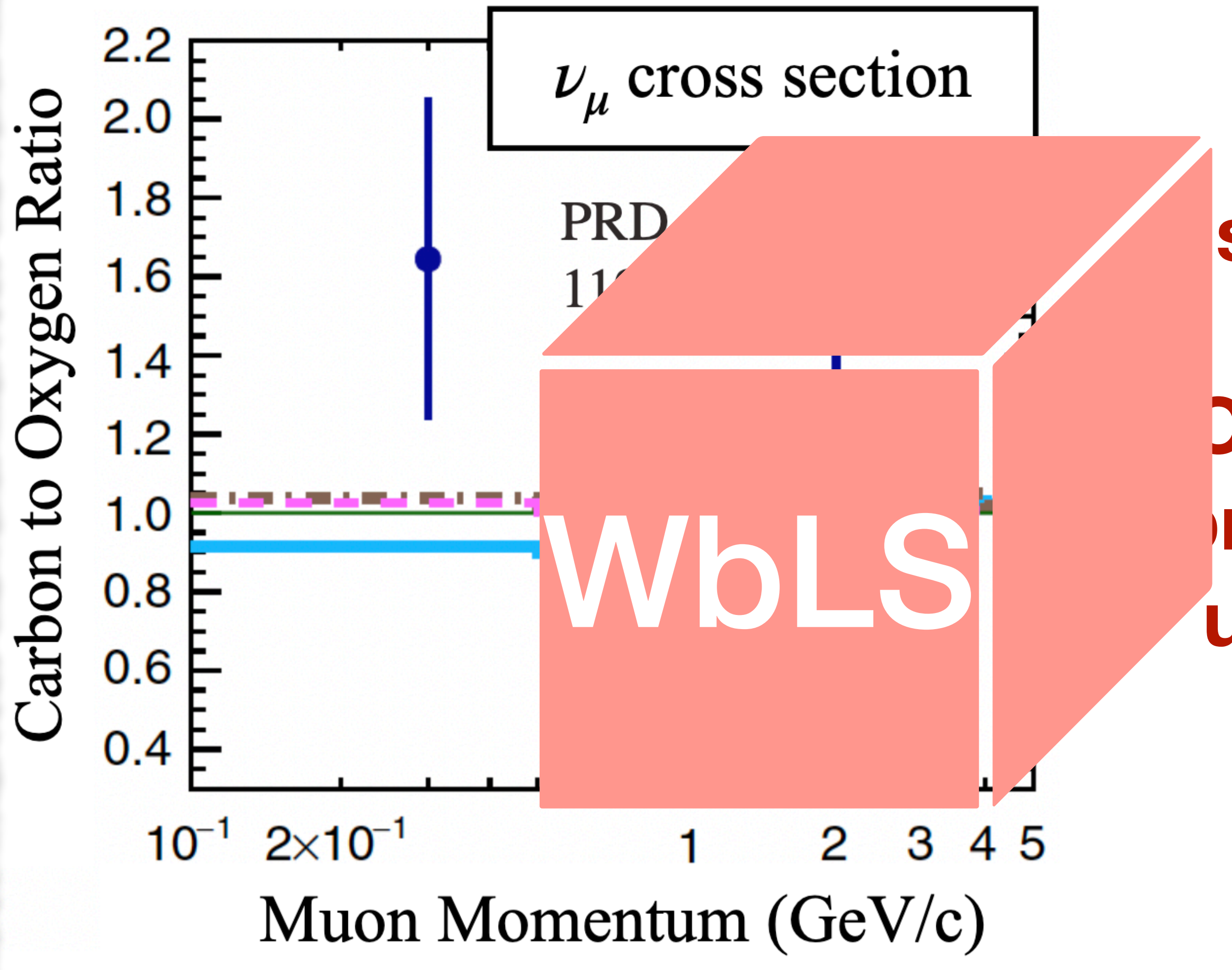

Scaling of cross-section model from Carbon (ND280) to Oxygen (SK/HK) also bring some additional uncertainties → add Water in ND280

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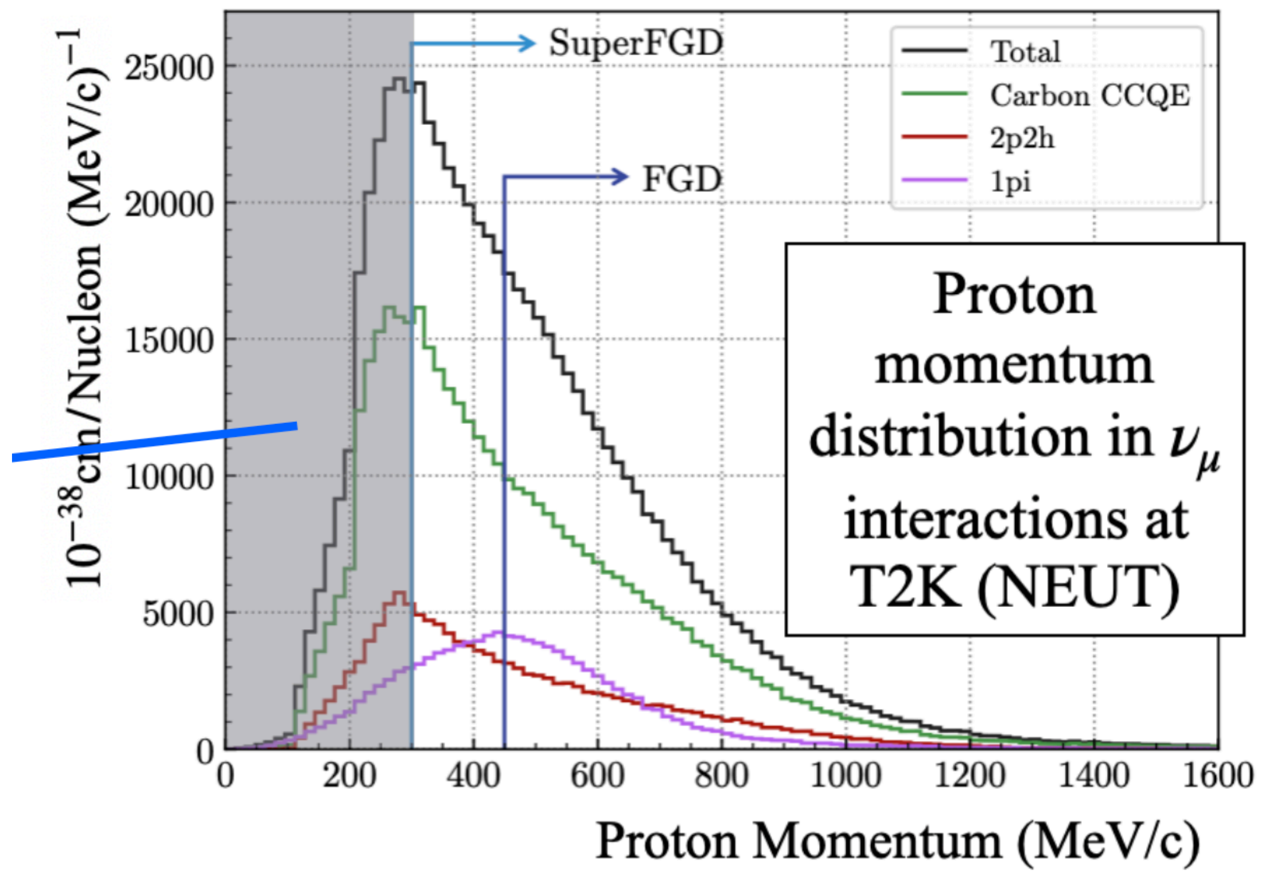
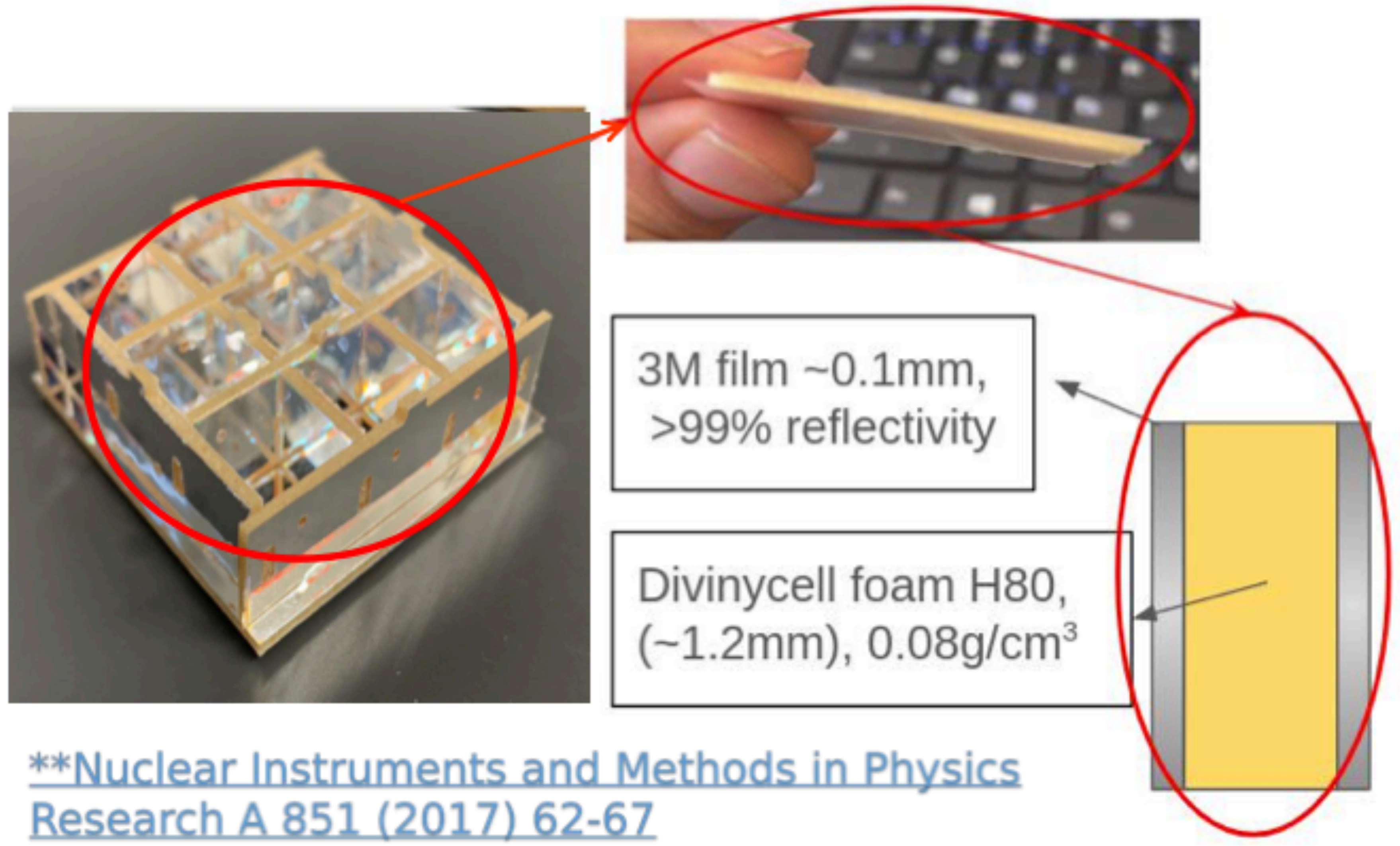


Water-Based Liquid Scintillator @ ETHZ



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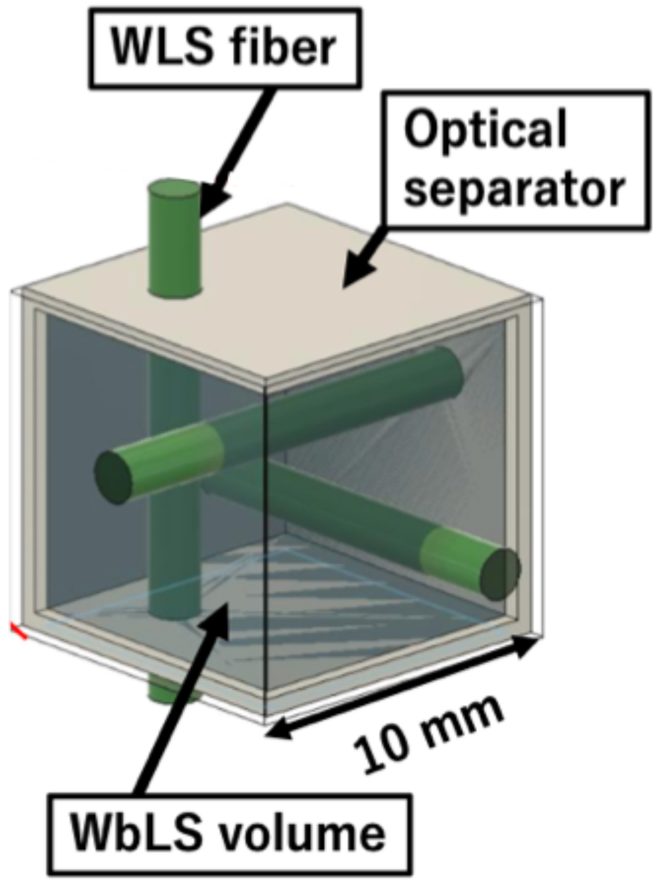
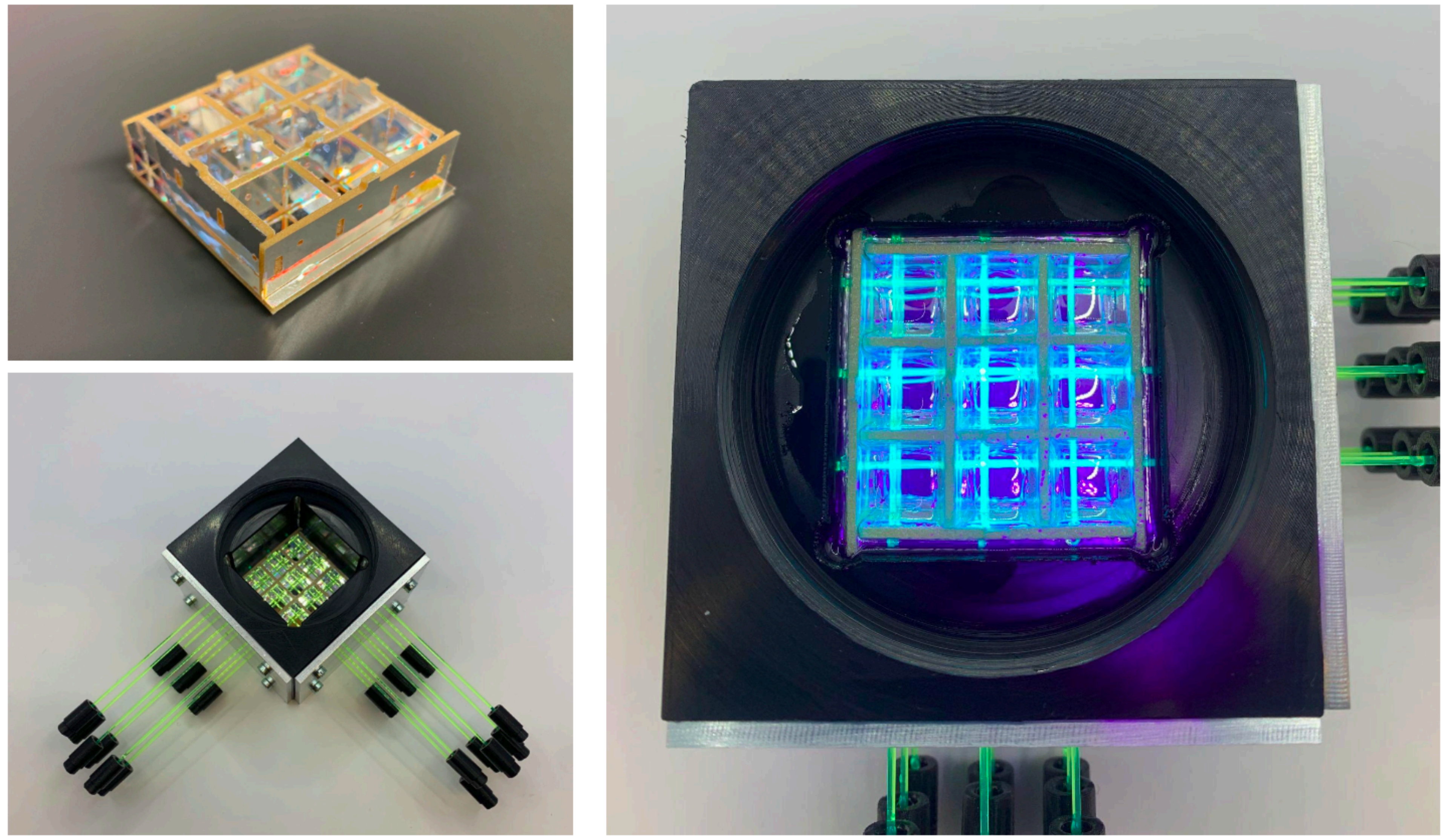
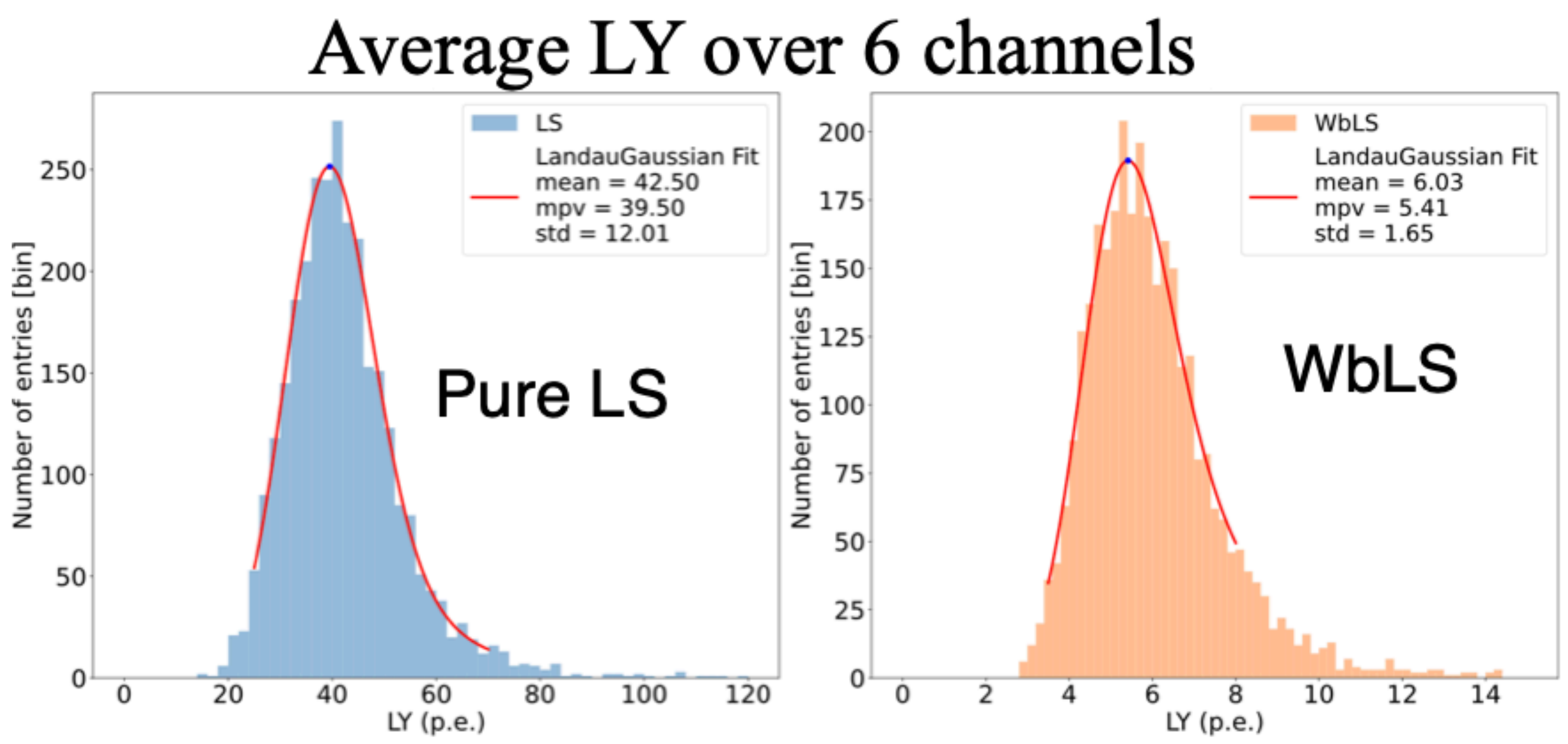


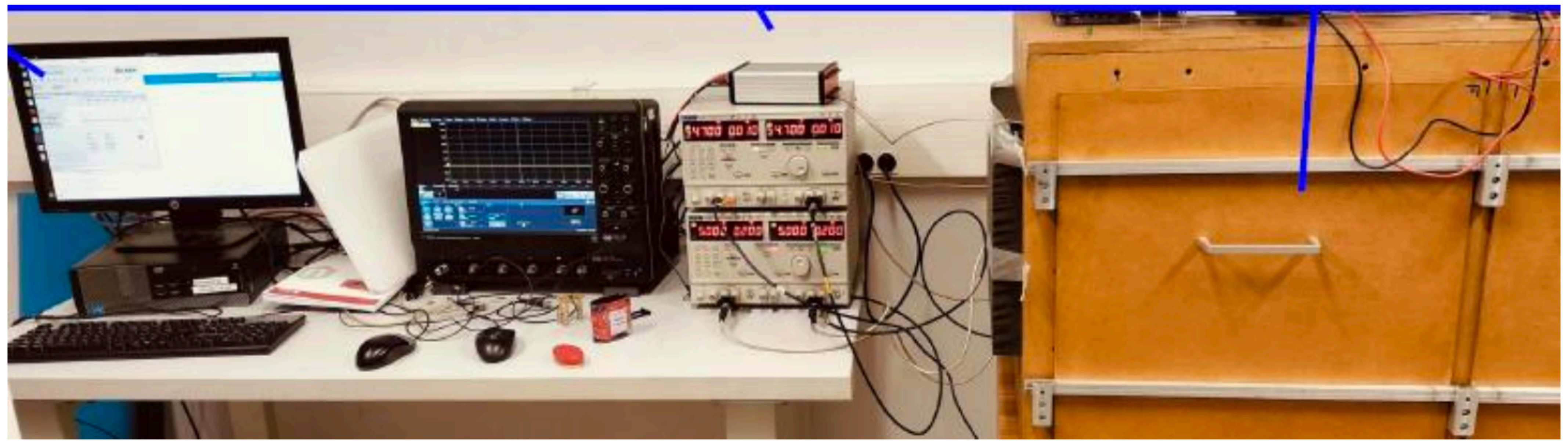
	<LY> per fiber	xtalk
LS	42.5 p.e.	2.3%
WbLS	6.0 p.e.	1.9%



- Similar design as the sFGD with high granularity and cubes-like structure
- Filled with Water-Based LS to measure neutrino interactions on water
- WbLS invented by M. Yeh (BNL) → NIM A660, 51–56 (2011), JINST 19 P01003 (2024)
- Our goal is to maximize water content in the detector → 90% H_2O, 10% LS (LAB+PPO+MSB)
- Paper submitted to JINST



LPNHE setup



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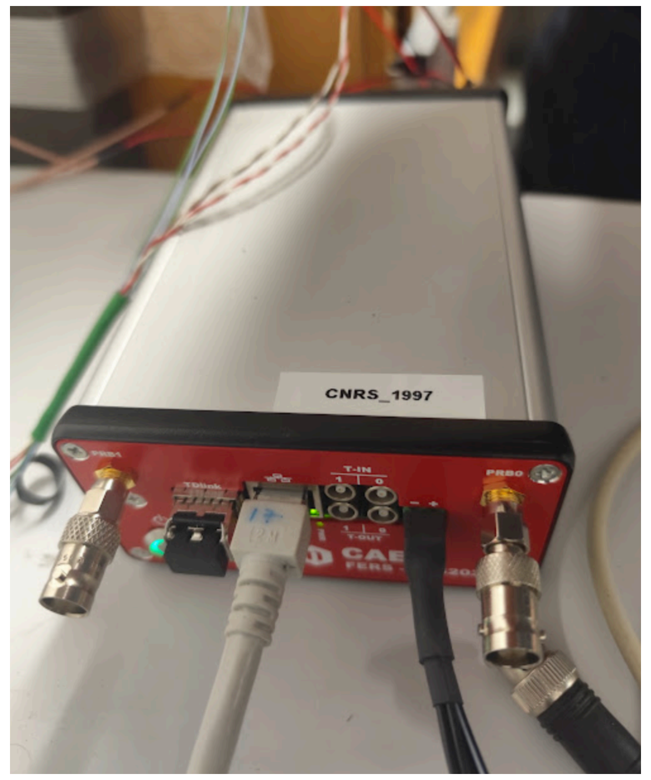
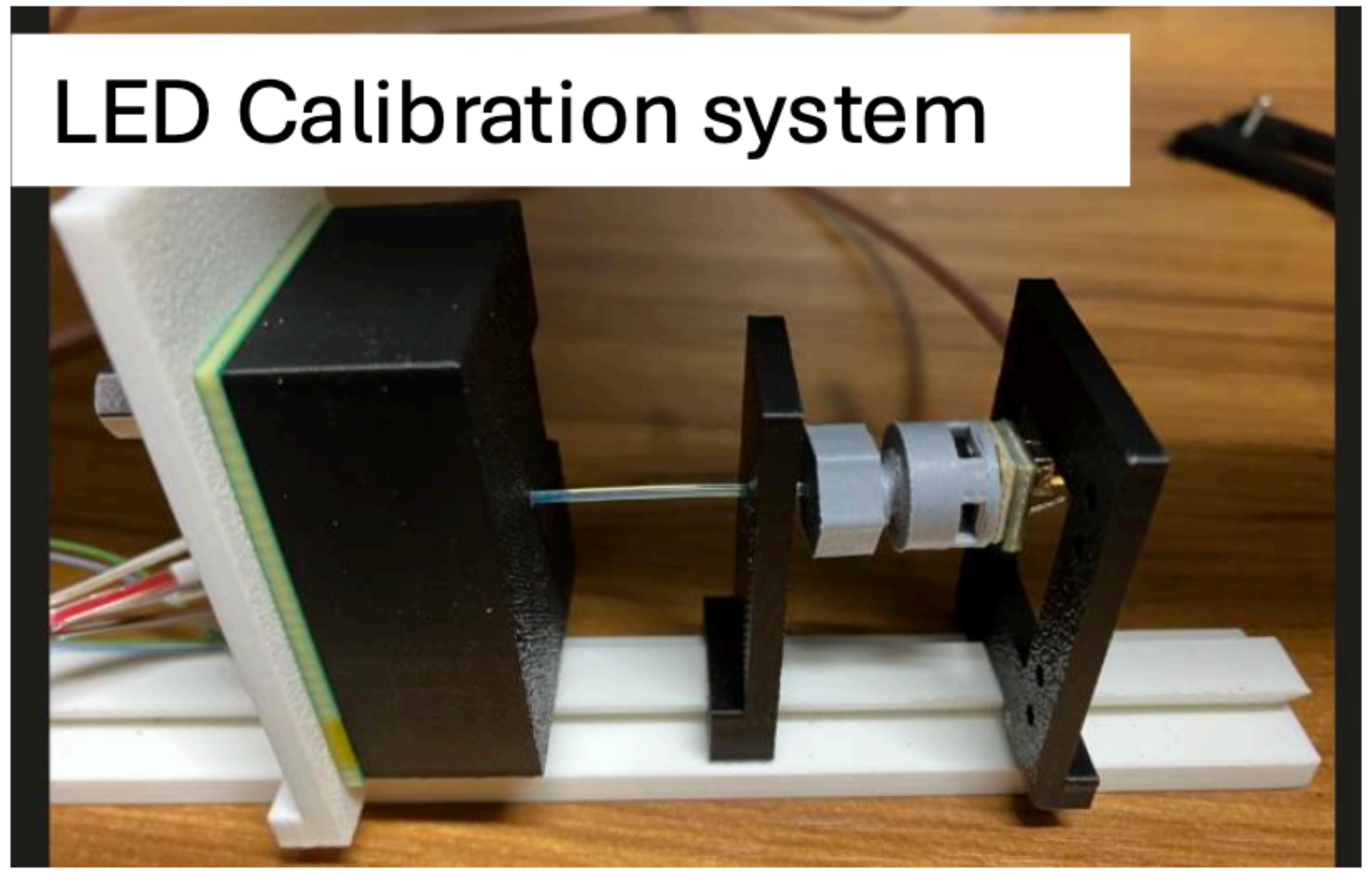
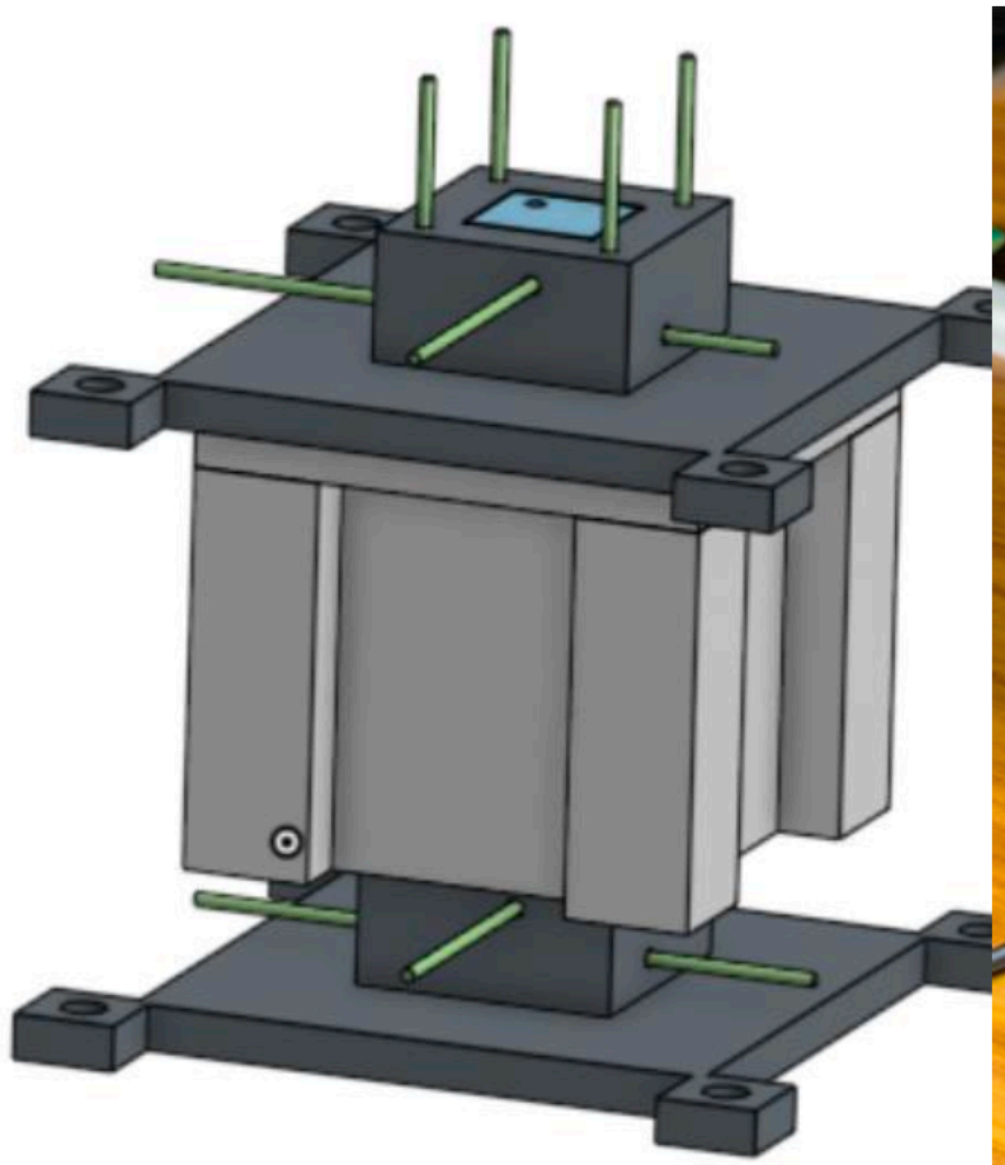
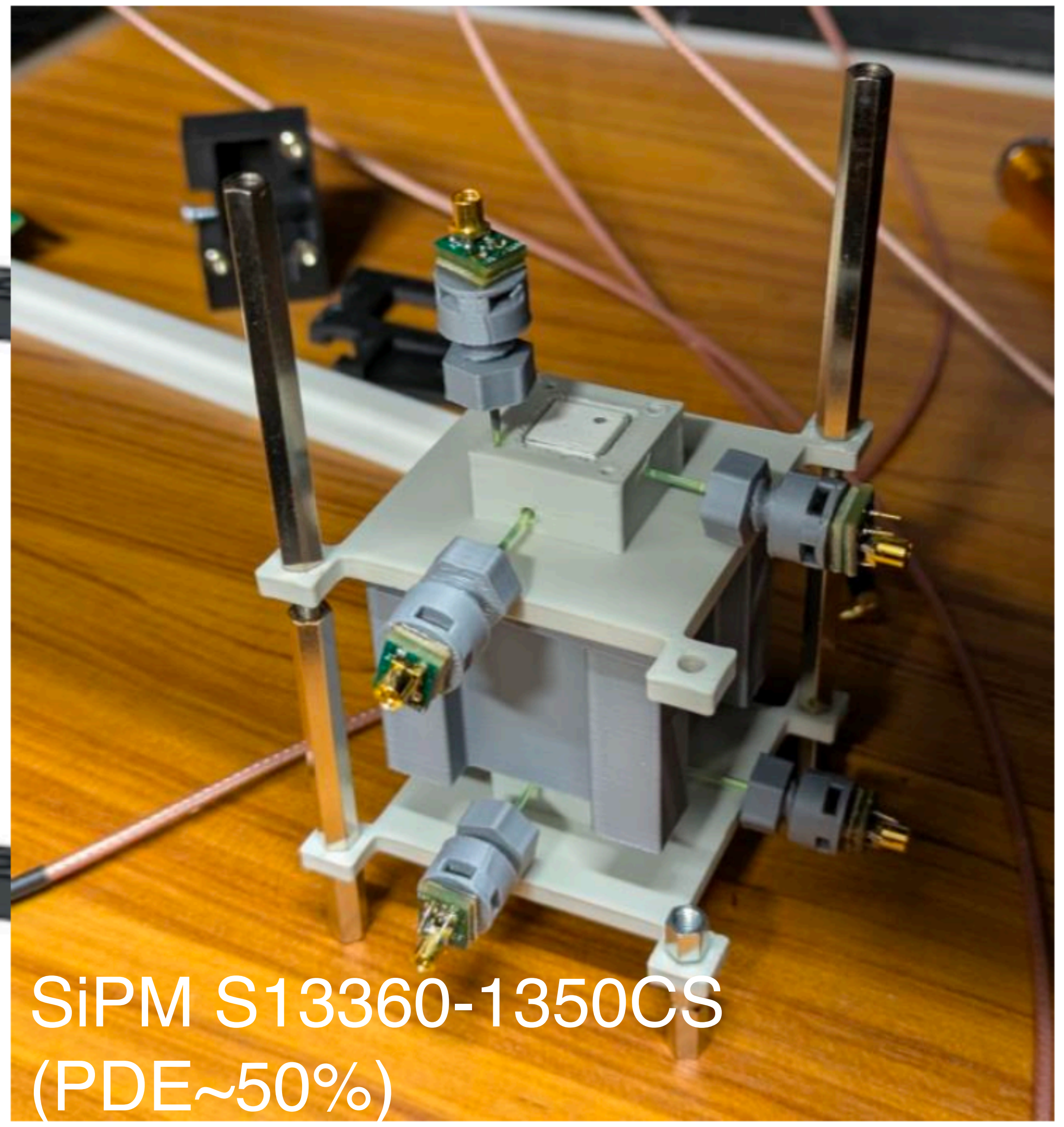


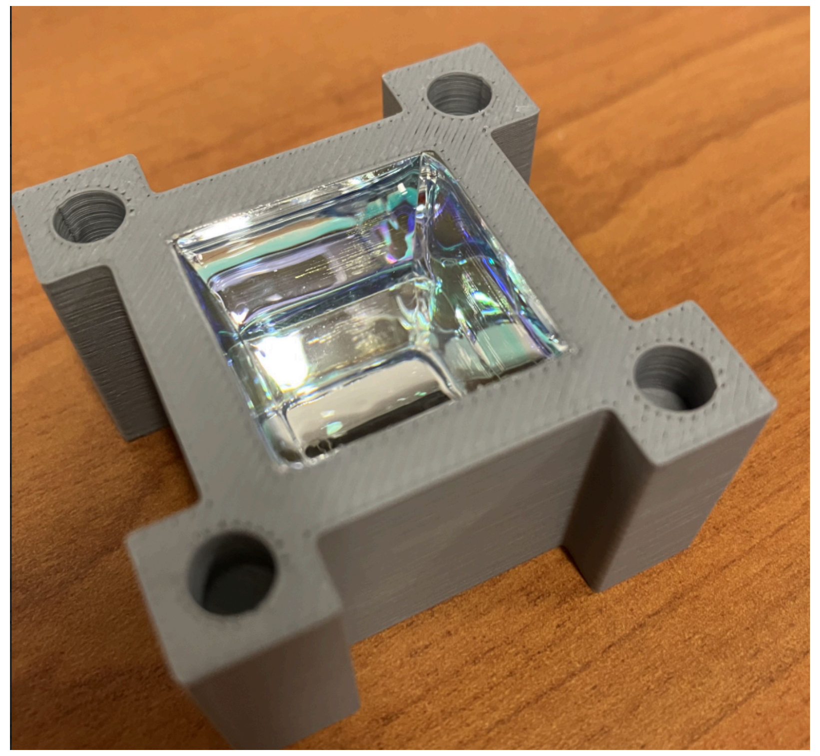


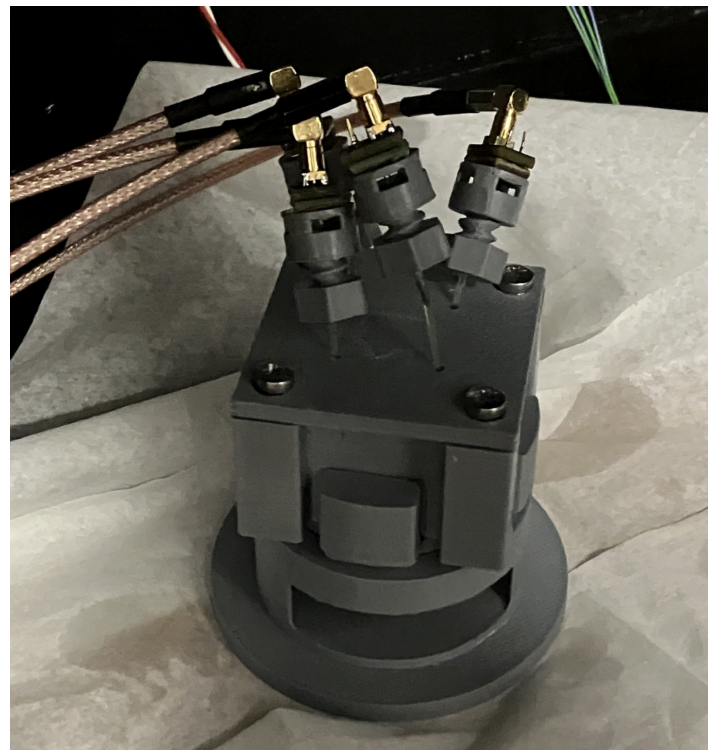
- With the first prototype we reached a LY of 6 p.e. / fiber / cosmic
  - Not enough, we would like to reach at least 20 p.e. keeping the same water content in WbLS
- Several ideas being investigated
  - Higher PDE SiPM
  - Different (more?) WLS fibers
  - Better reflectivity
  - Better SiPM/fibers coupling





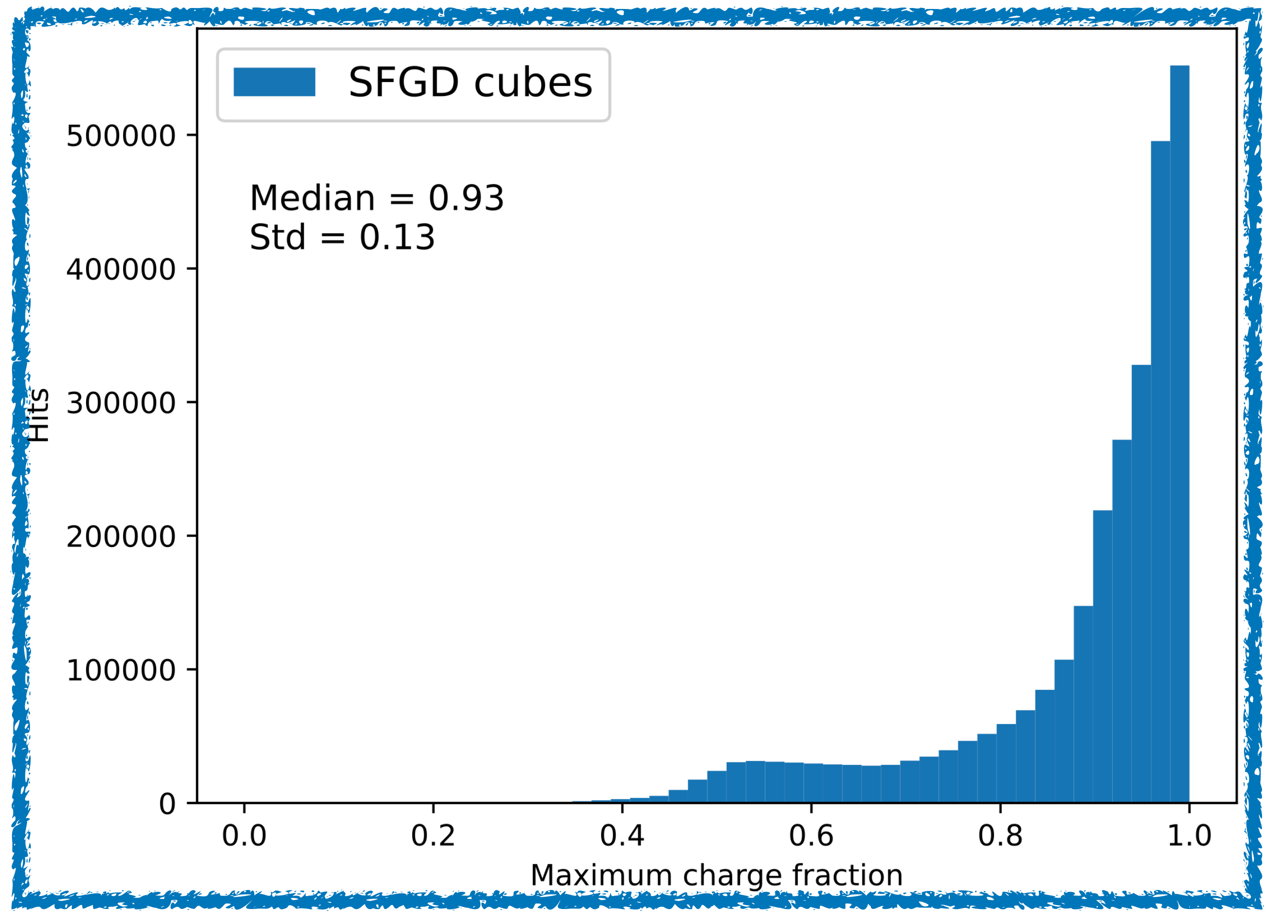
Preliminary results



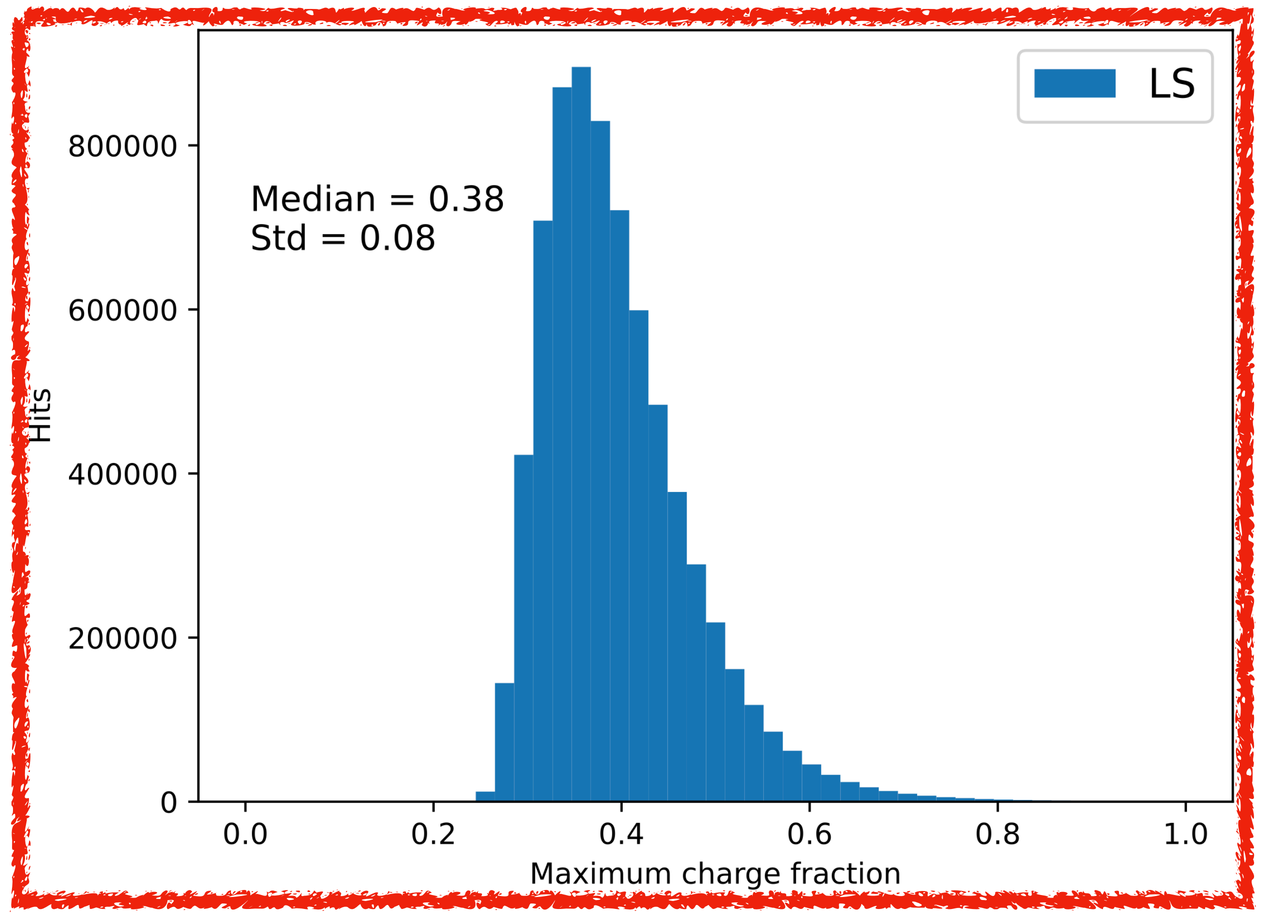


- 3D printed a 8 cm^3 “SuperCube” with 3M reflector
  - Filled with SuperFGD cubes
  - Pure LS
  - WbLS
- Readout with 4 WLS fibers and SiPM
- Tested with a ^{90}Sr source

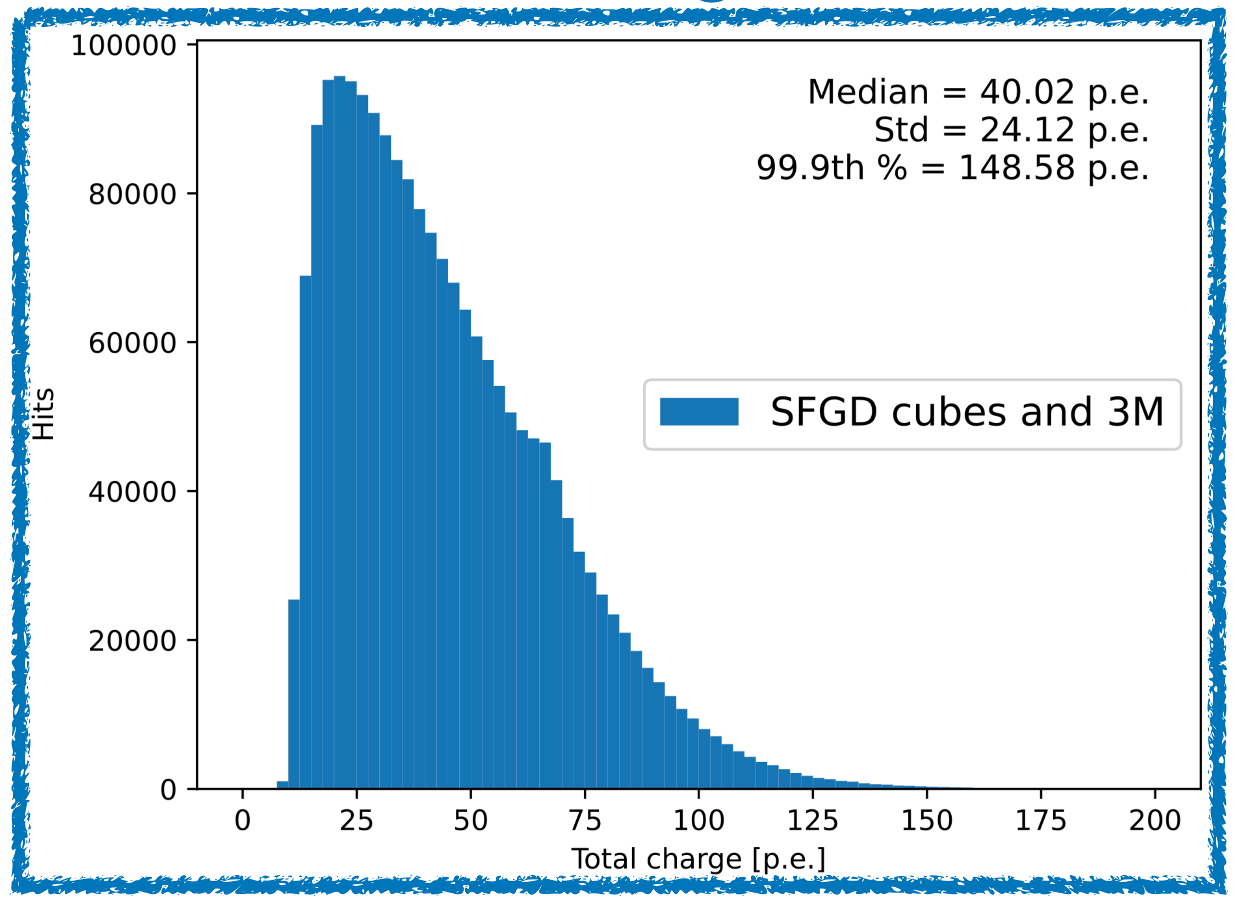
Charge Fraction



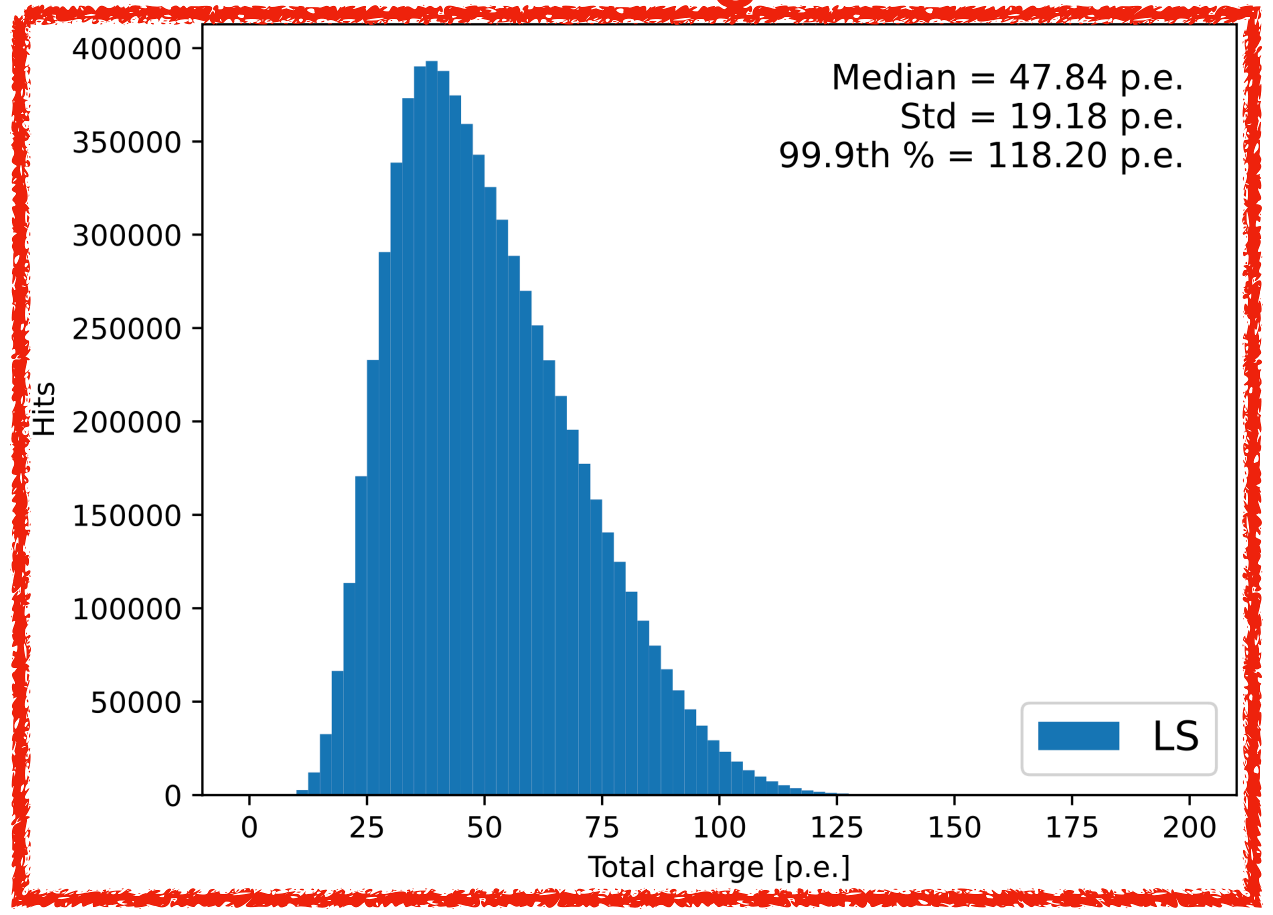
Charge Fraction



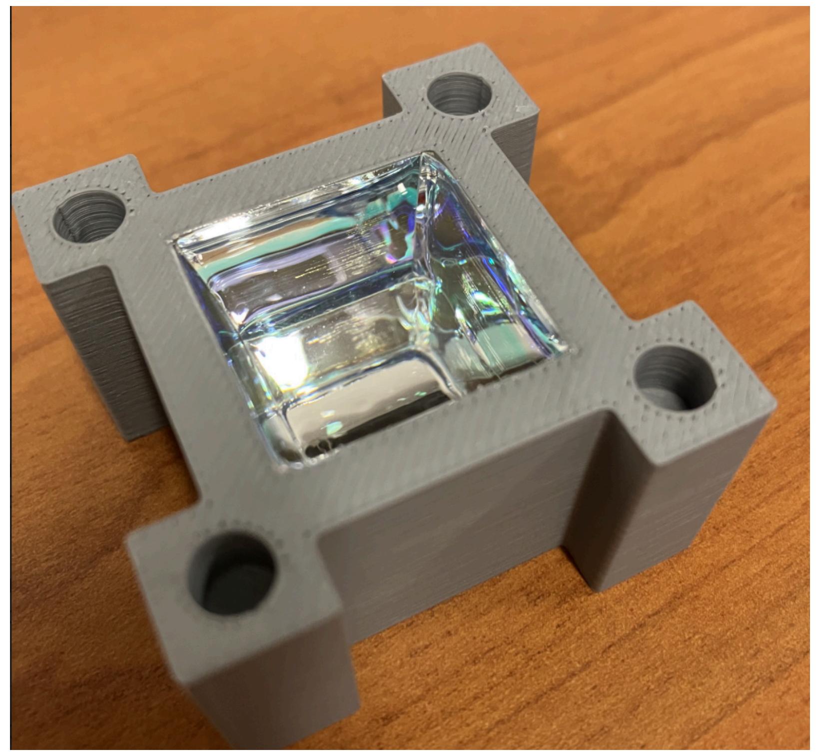
Total Light

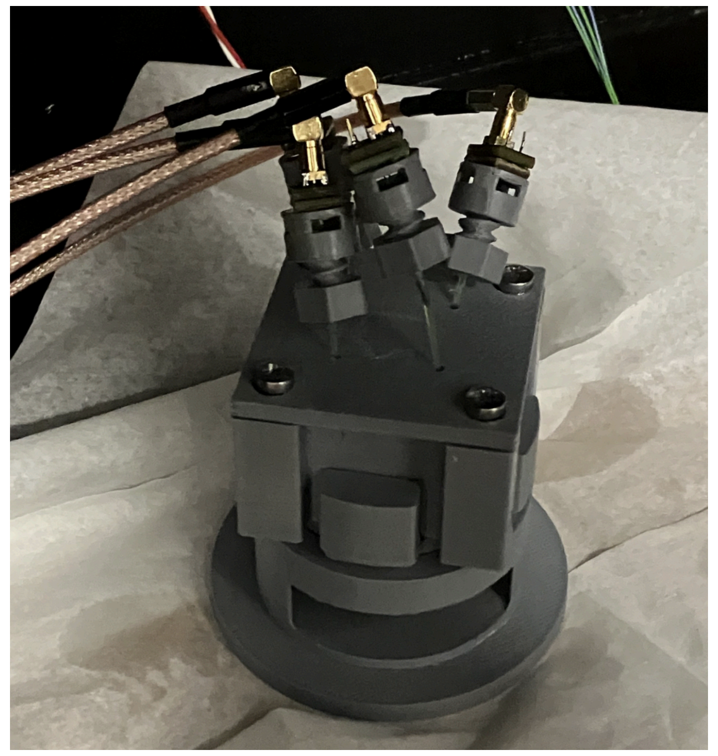


Total Light

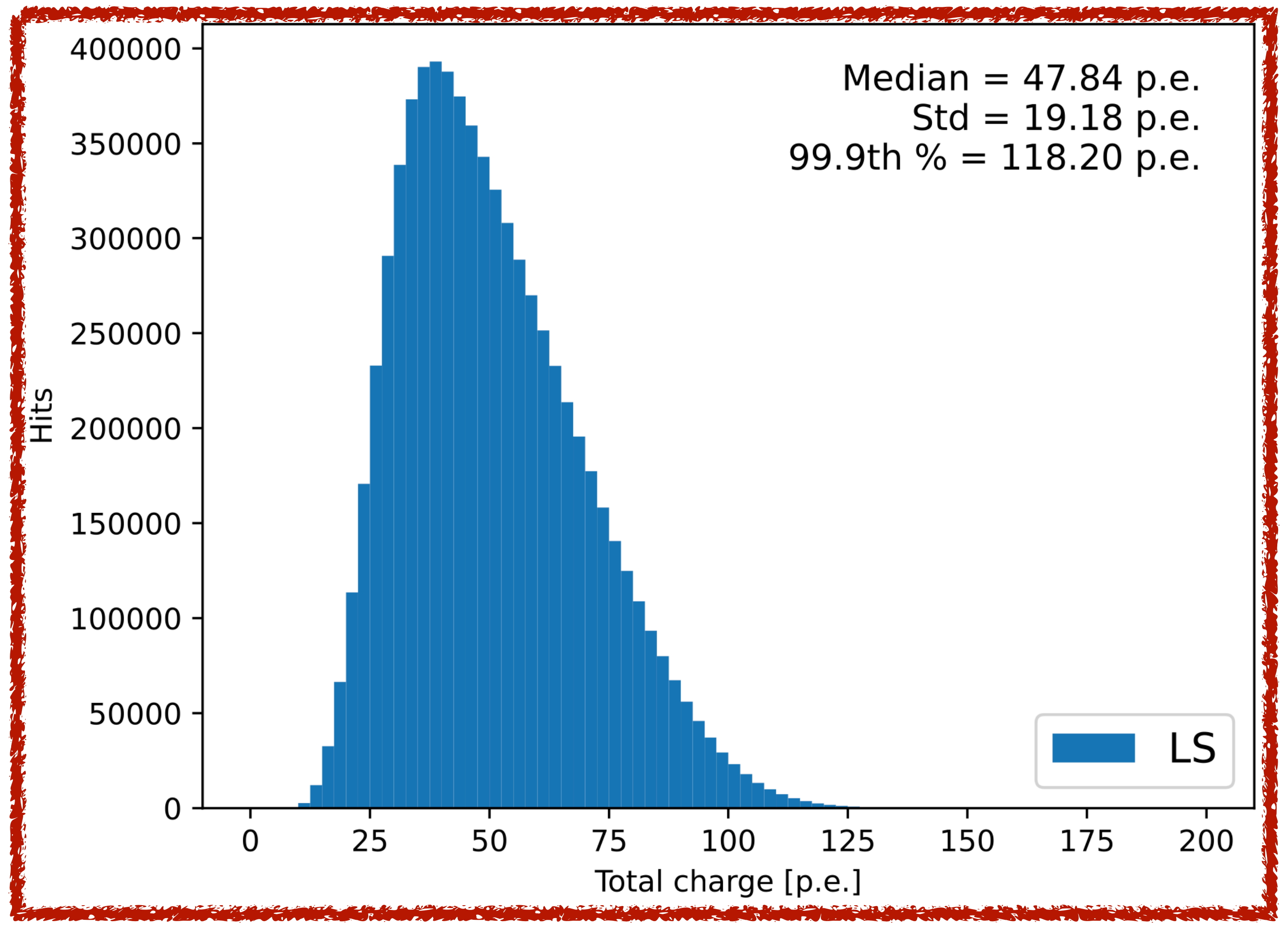


Preliminary results

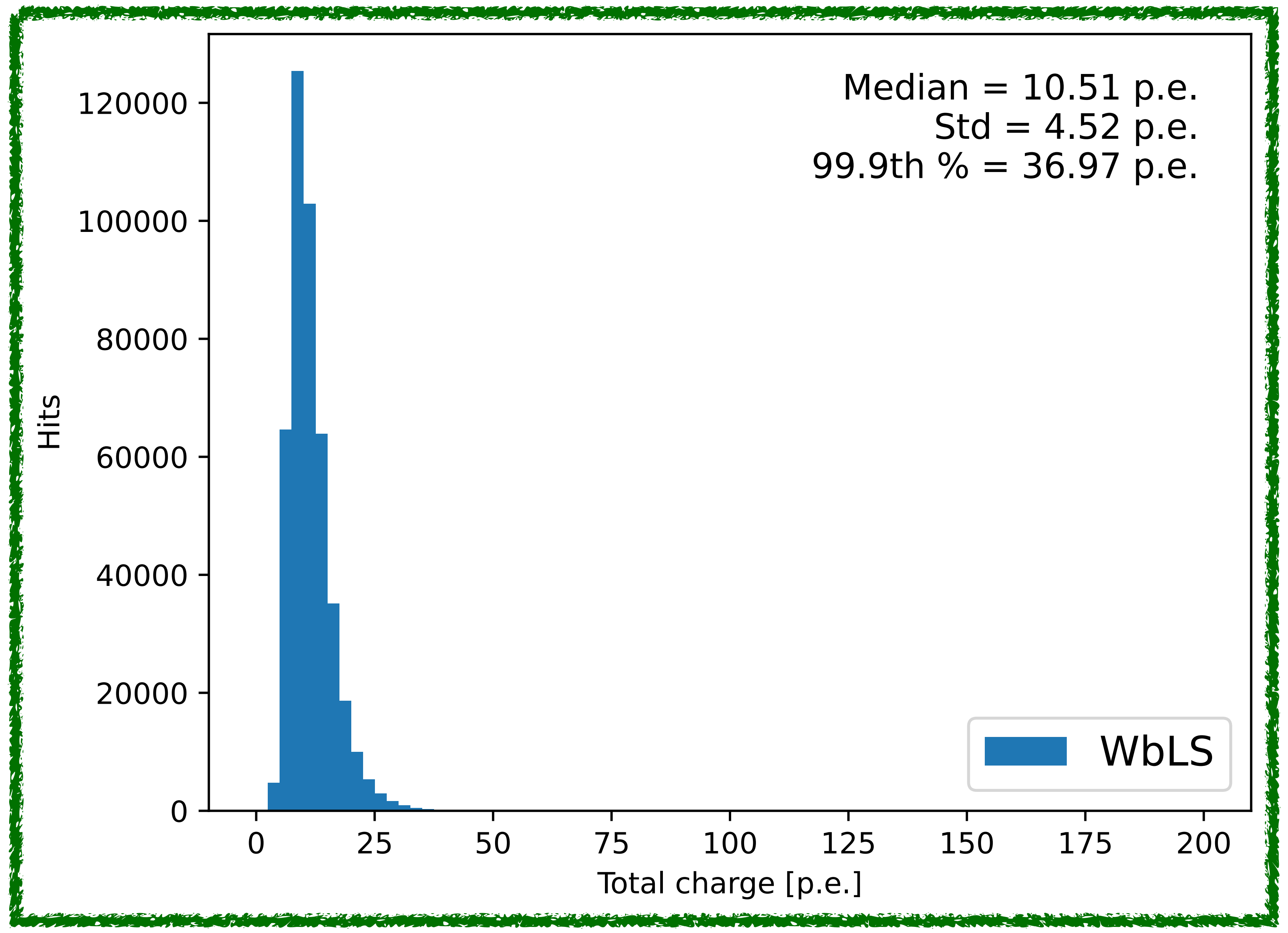




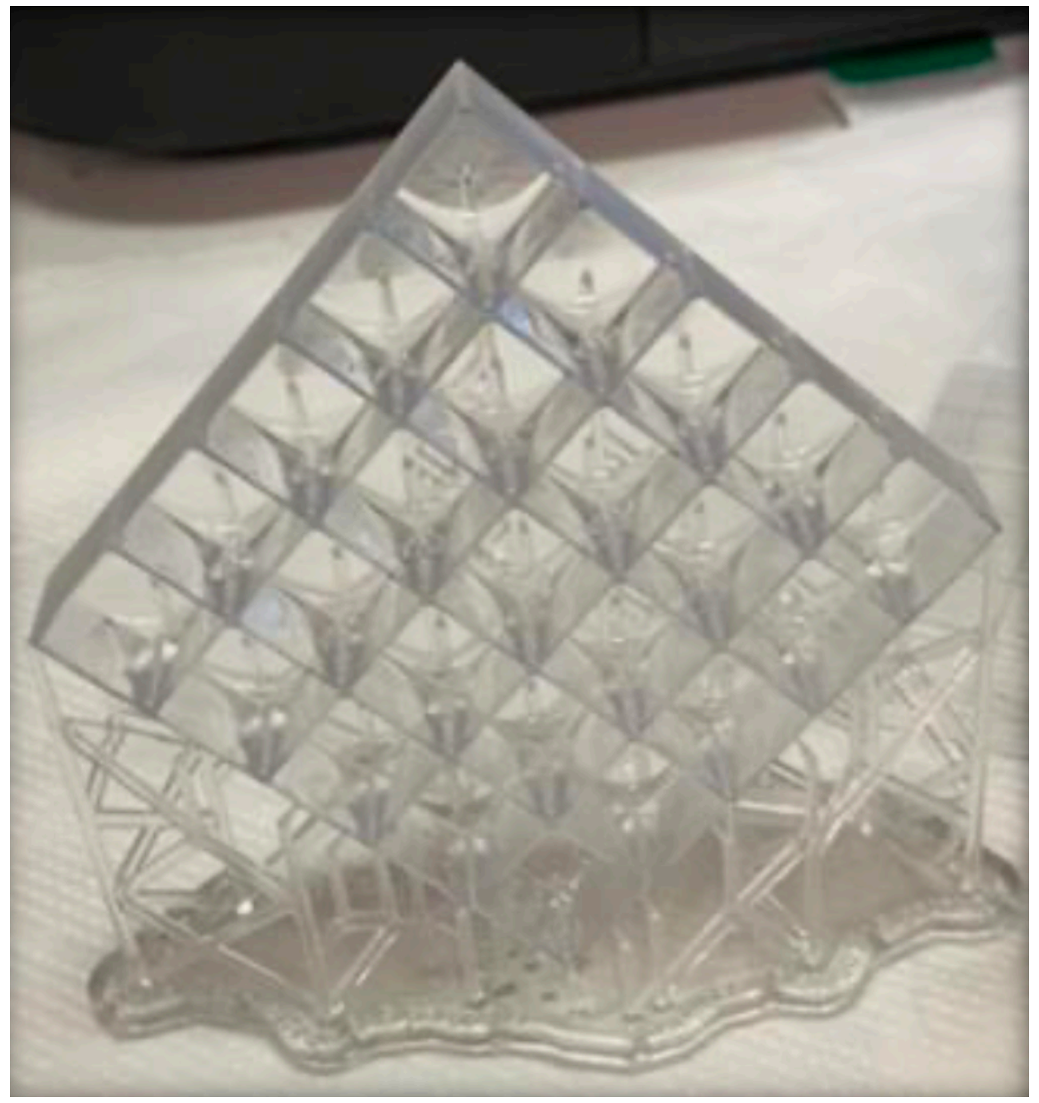
- 3D printed a 8 cm^3 "SuperCube" with 3M reflector
  - Filled with SuperFGD cubes
  - Pure LS
  - WbLS
- Readout with 4 WLS fibers and SiPM
- Tested with a ^{90}Sr source

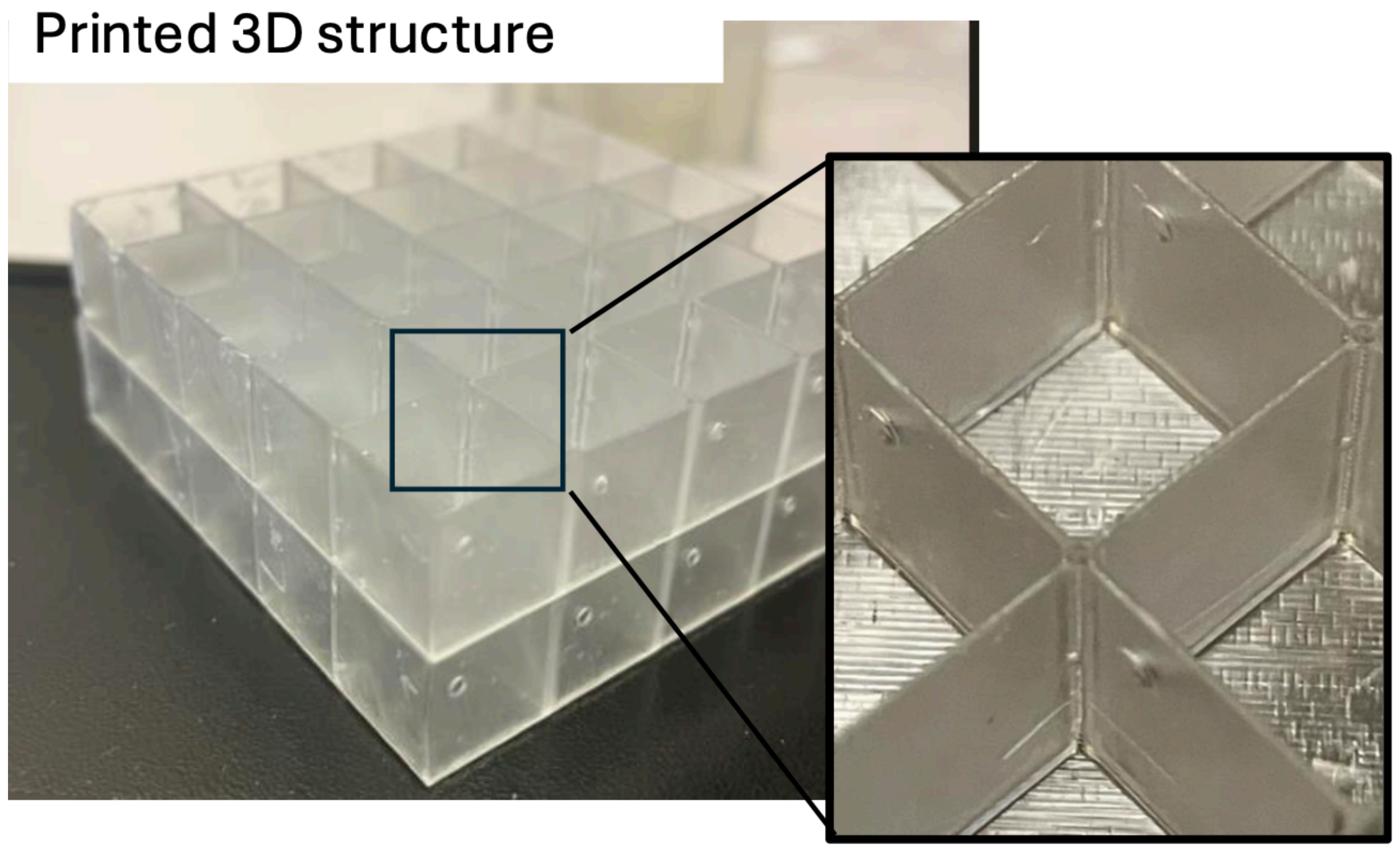


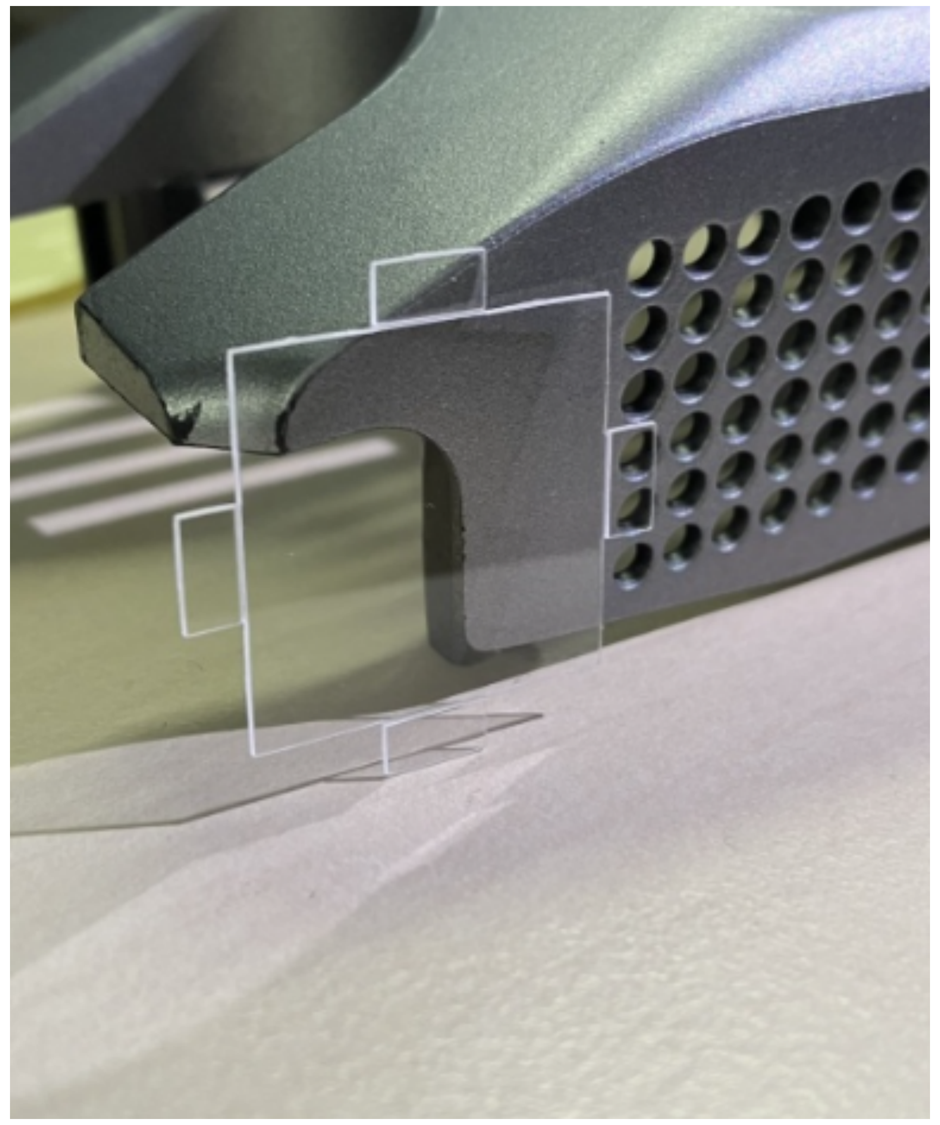
Factor of ~5 lower LY for WbLS than LS



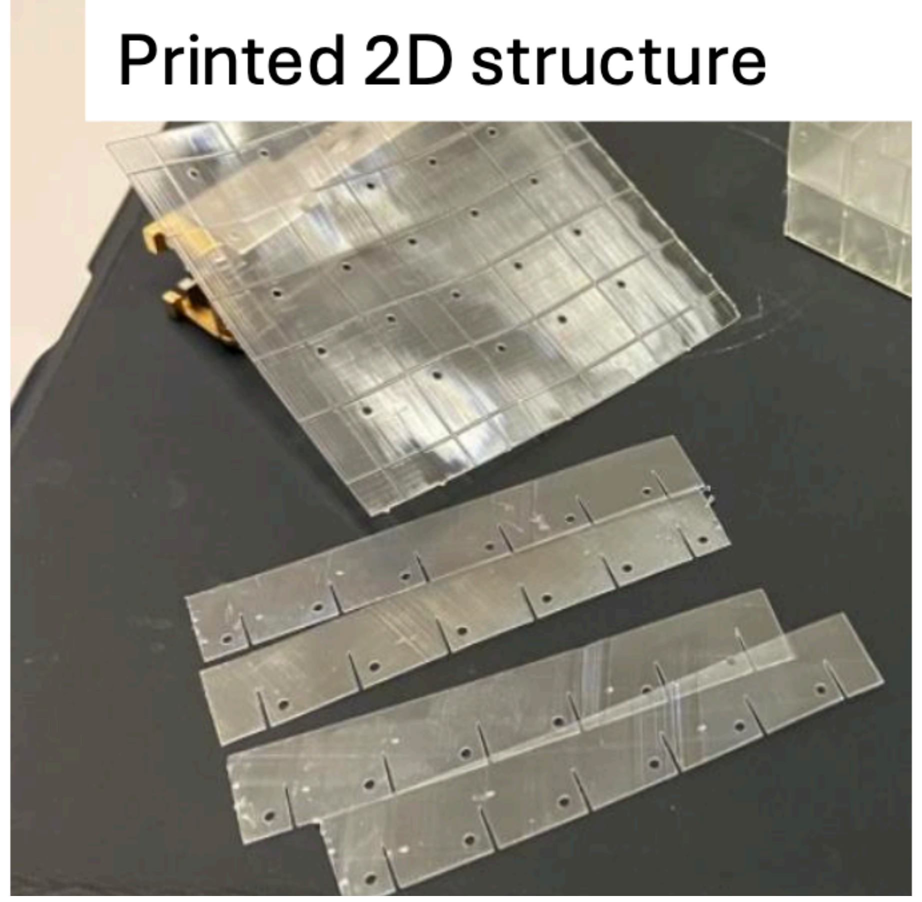
Reflectors





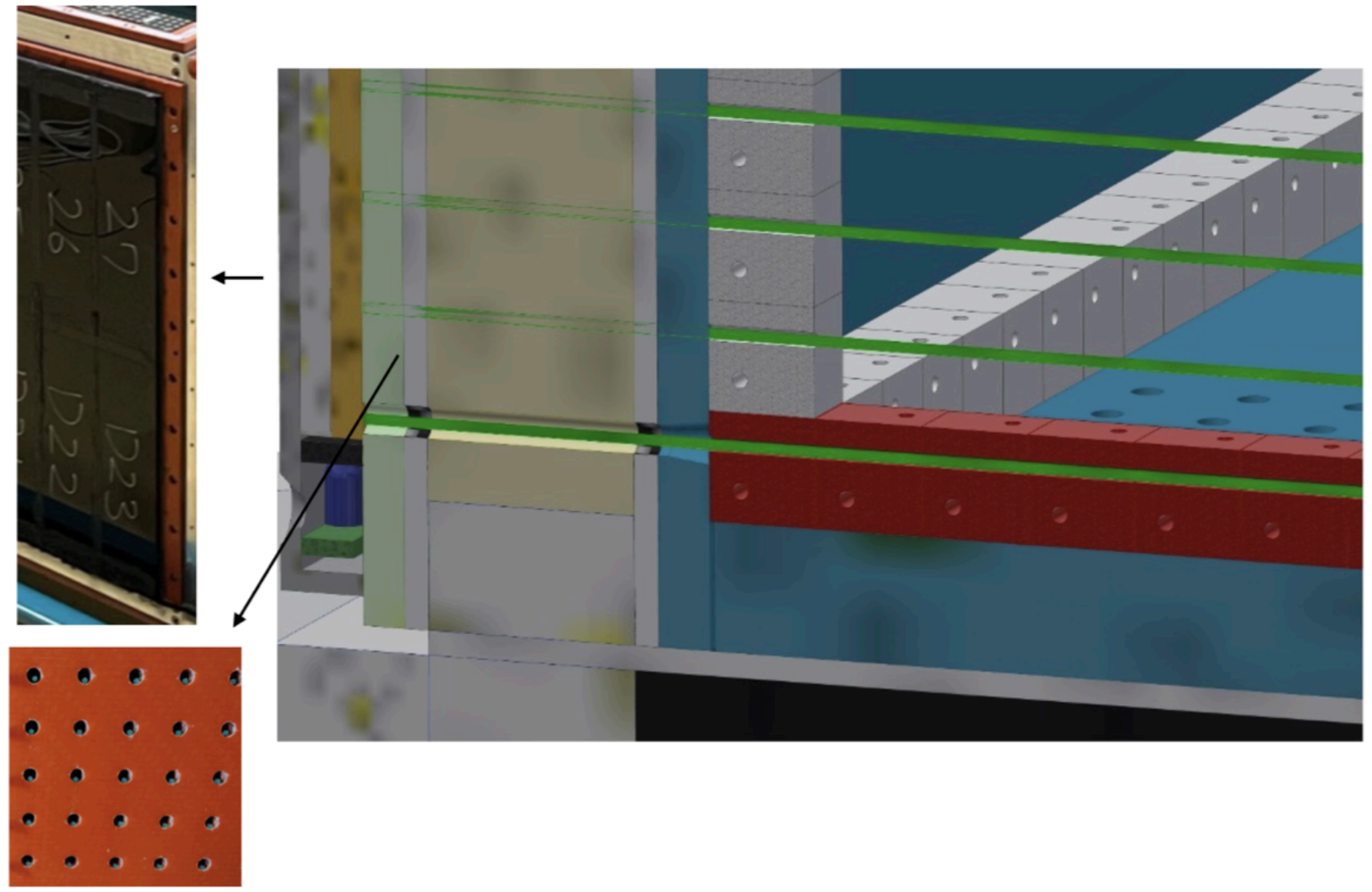


- Divinycell+3M has some disadvantages:
  - Large volume occupancy
  - Difficult to assemble on large scale
  - Dependence of the reflectivity on the photon angle

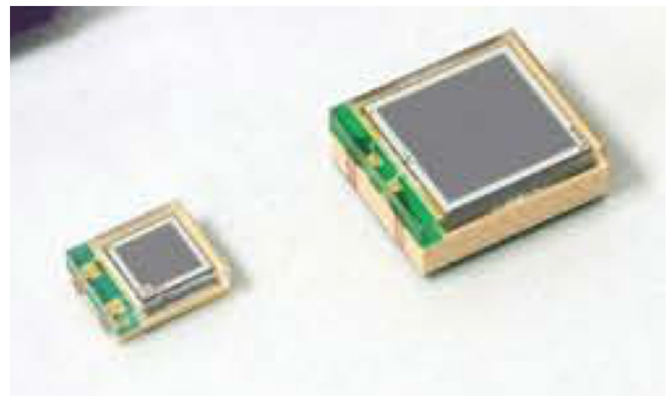


- We are investigating the feasibility of doing dielectric coating on PMMA or 3D printed surfaces
  - Collaboration with LMA (Laboratoire Materiaux Avancés)
  - Hope to have results soon!

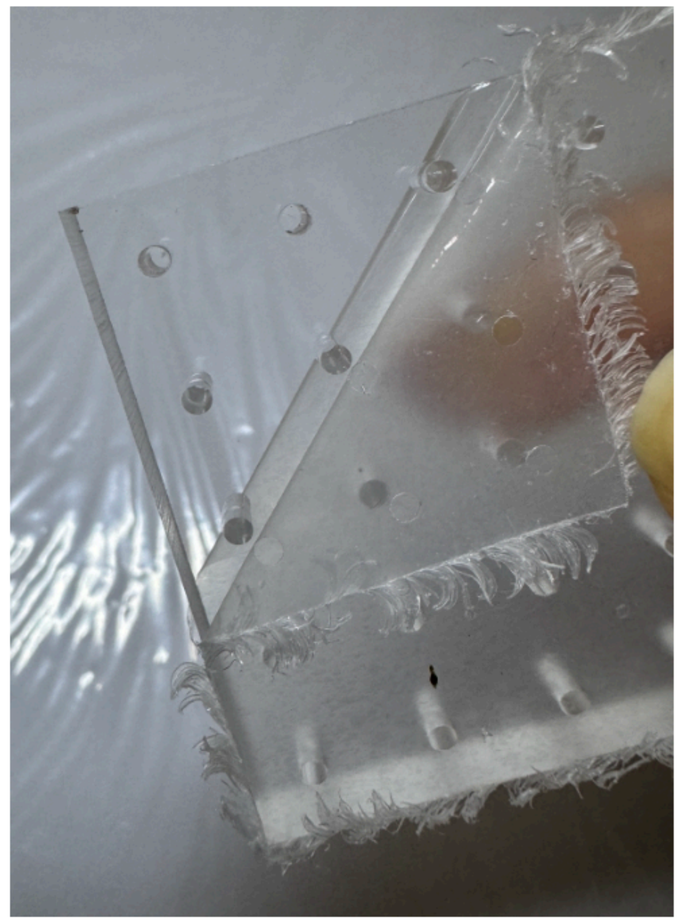
Fibers/SiPM coupling

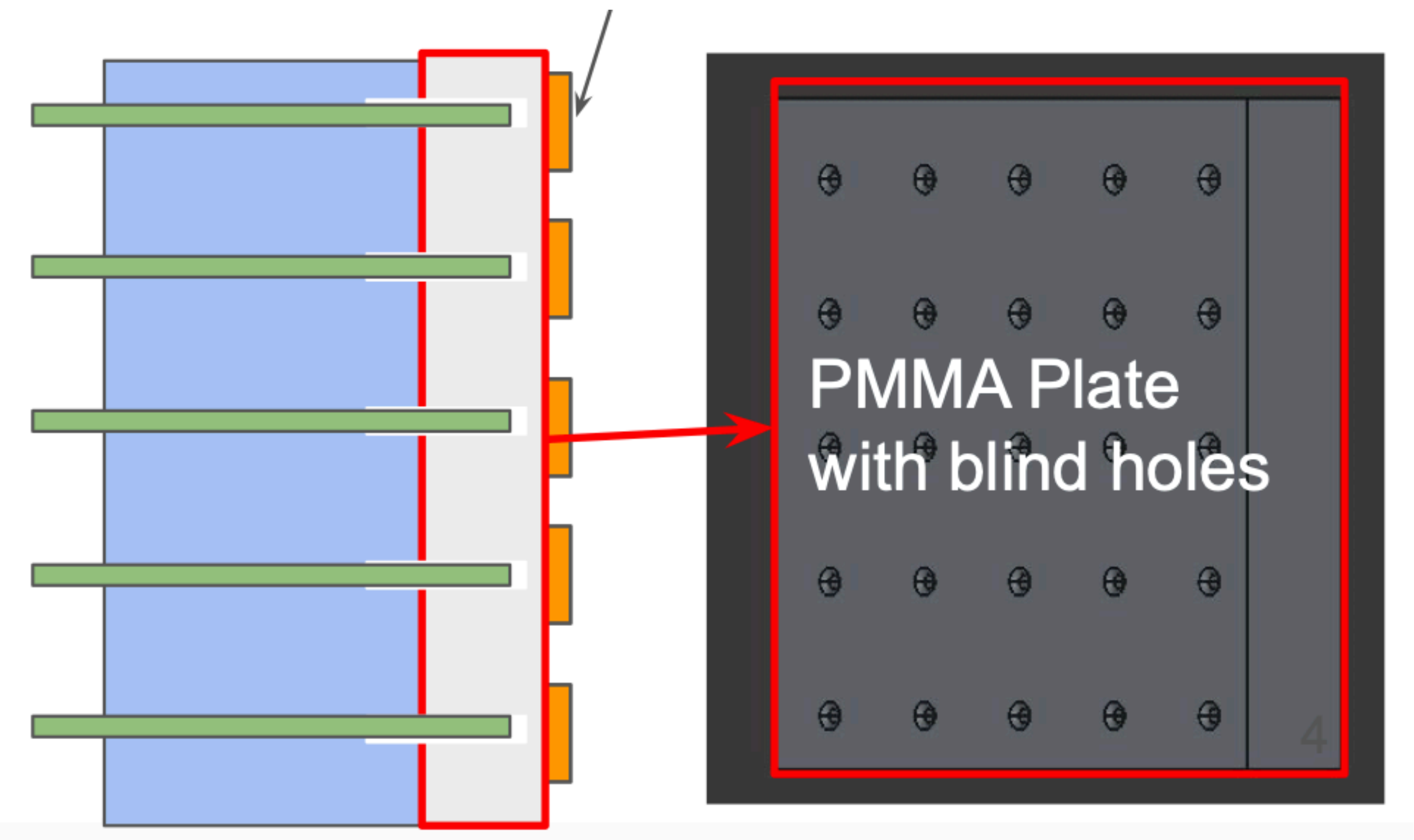


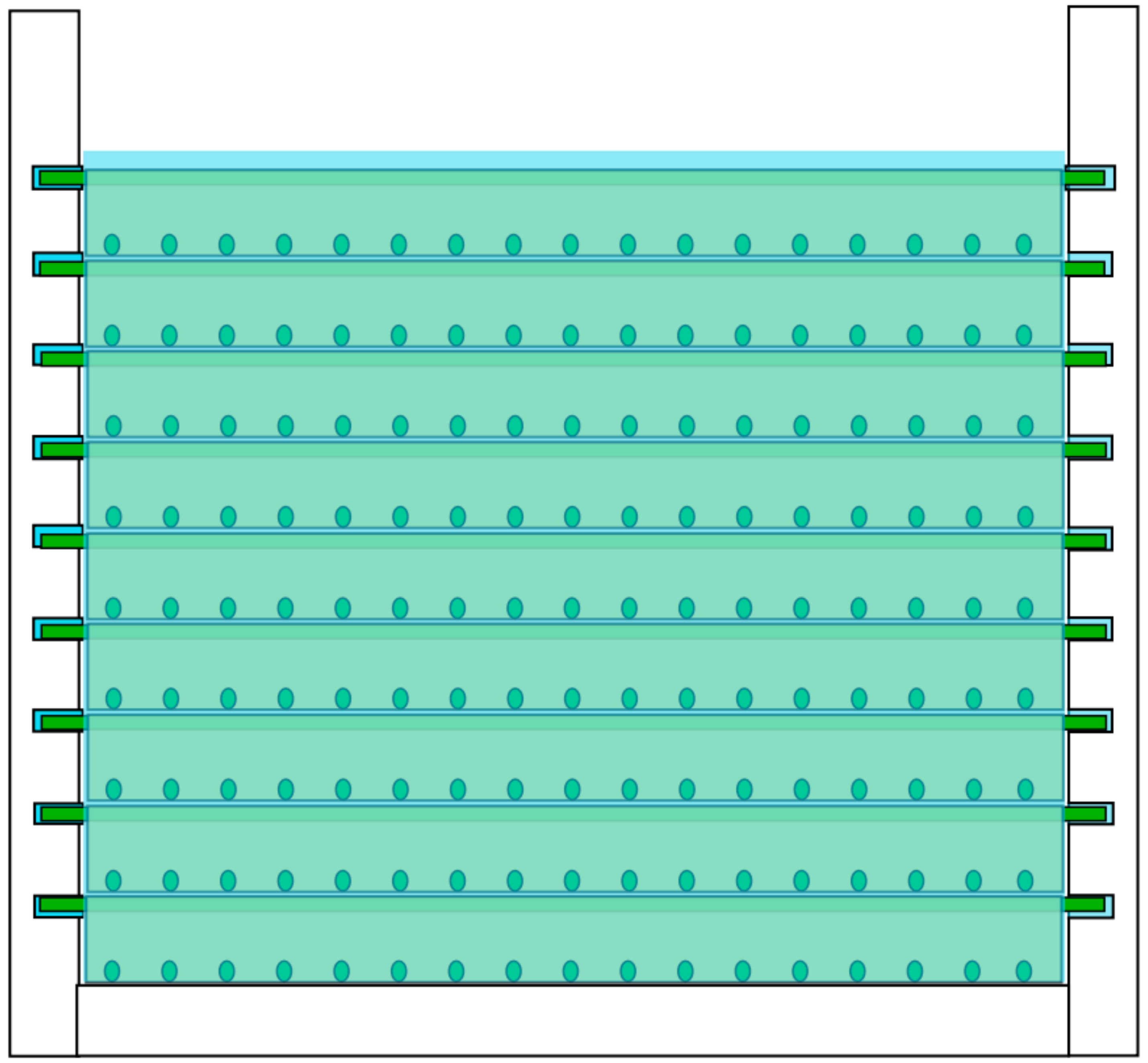
Larger SiPM (3 mm)



Vacuum thermoforming

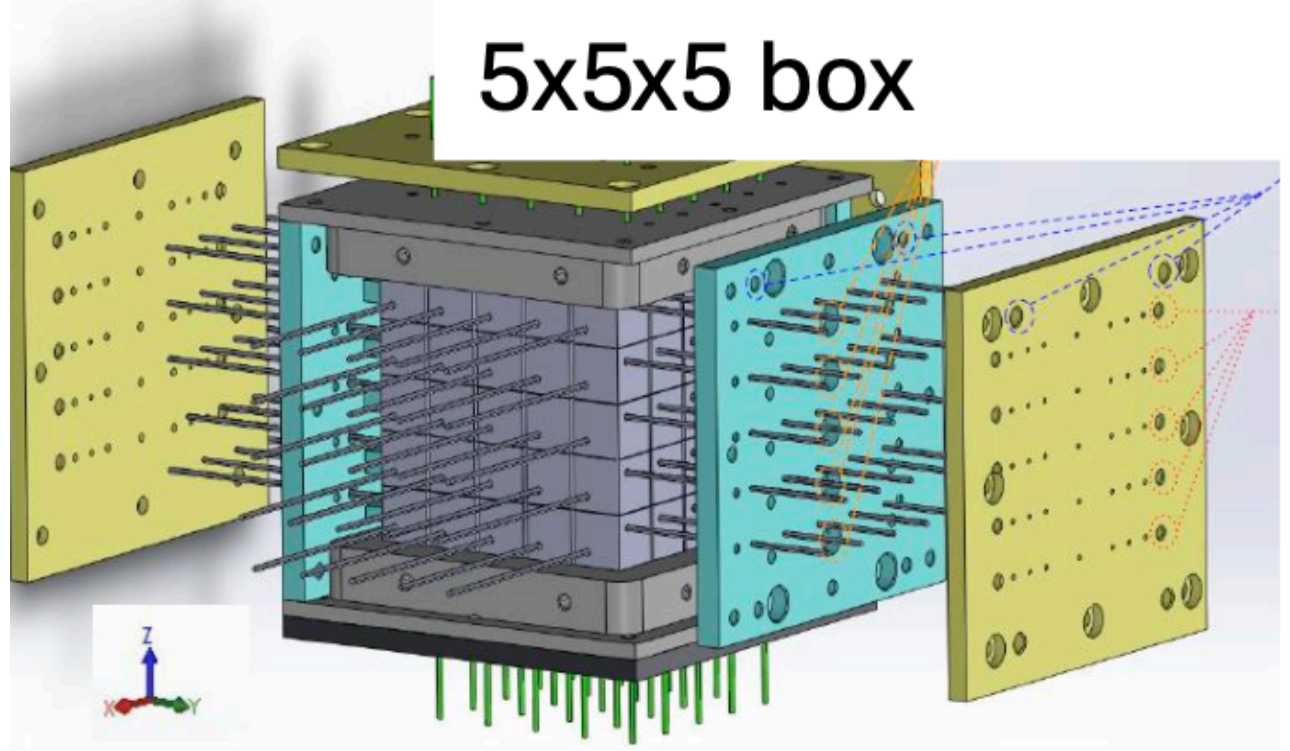




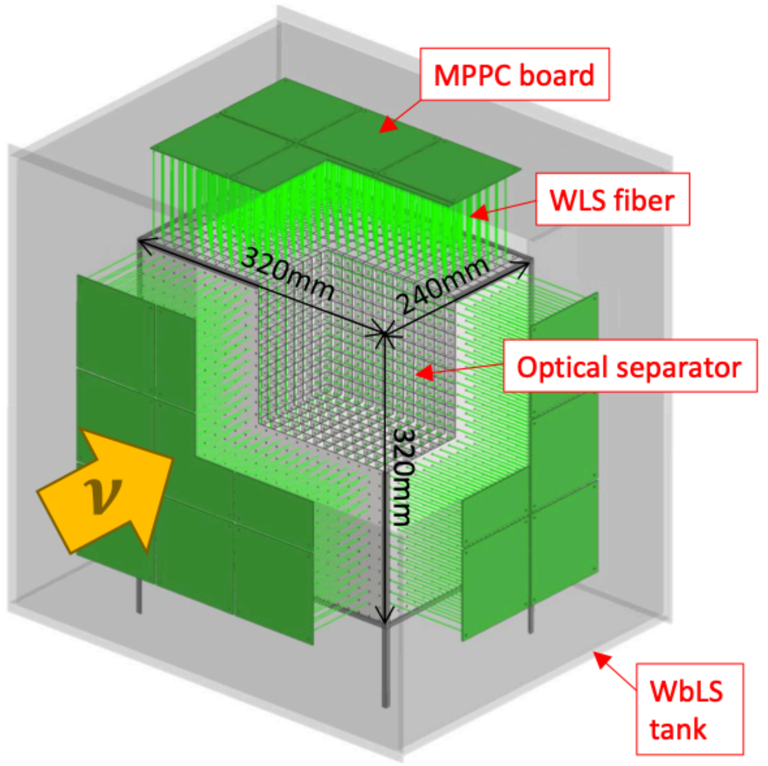


- In the case of the super-FGD the WLS fibers exit the box and are coupled to SiPM
  - No need to be water tight
- For WbLS we are studying how to keep fibers inside the box (no holes) and do the coupling with SiPM

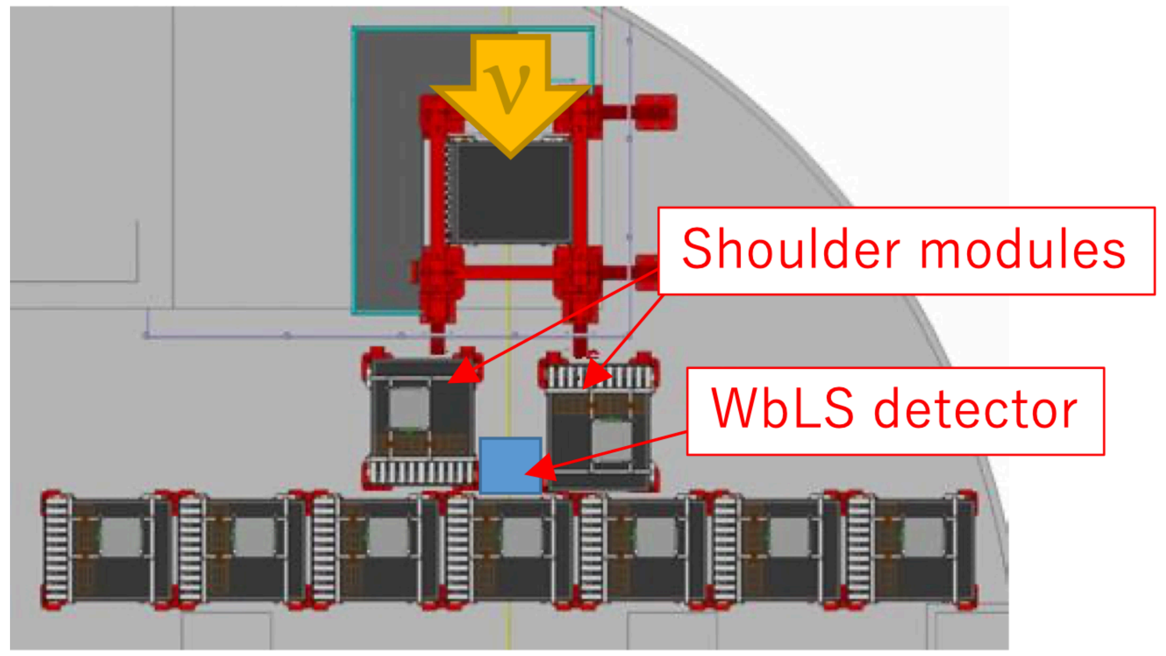
Conclusions and plans

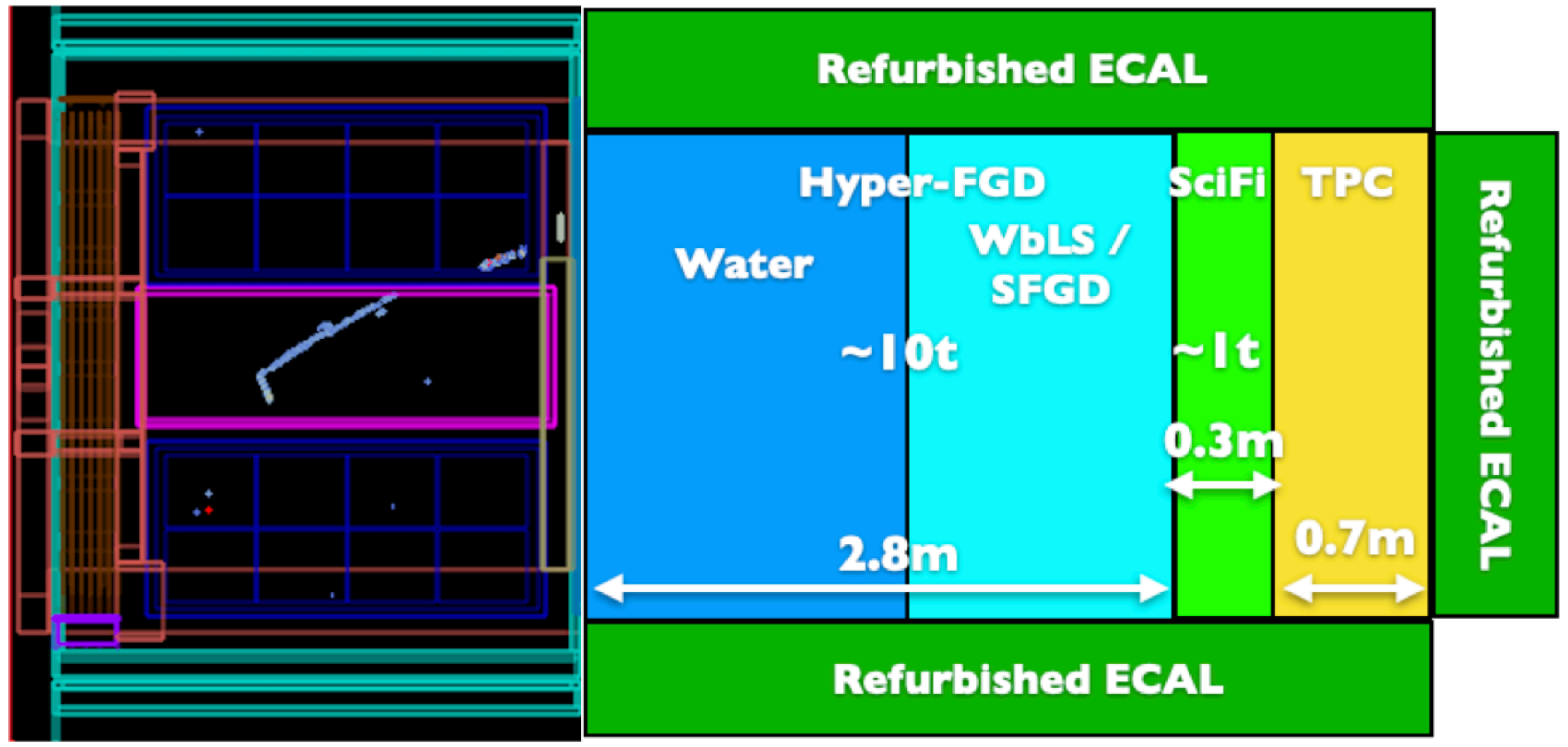


- Maximize LY on few cm scale detectors
- Design an integrated mid-scale version (~30 cm size)
  - This prototype will be exposed to the J-PARC ν beam in 2027
  - Design it in such a way to be scalable to large size (~10 ton)
- Build final detector for ND280++ in 2031



or smaller one (240mm × 240mm × 160mm, ~1300 channels)





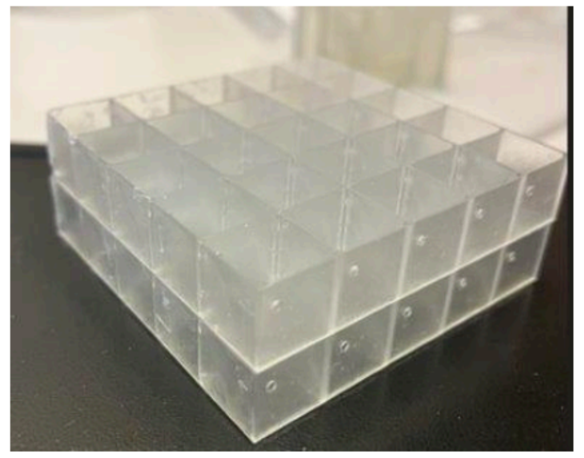
Back-up

Current solution Divinicell + 3M:

- Mass budget per cube:
  - Divinicell = 2.9e-2 g
  - 3M tape: 1.5e-1 g
    --> 15.2% of mass (structure/total)
- Volume occupation:
  - Divinicell: 1.2mm / 2
  - 3M tape: 66um
    --> 28%

Alternative resin + coating:

- Mass budget per cube:
  - resin= 1e-1 g
  - coating: 3.2e-3 g
    --> 10.4% of mass (structure/total)
- Volume occupation:
  - Resin: 0.3 mm / 2
  - coating: ~1um
    --> 8%



Coating